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Validation of Fire/Smoke Spread Model (CFAST) Using Ex-USS SHADWELL Internal Ship Conflagration Control (ISCC) Fire Tests

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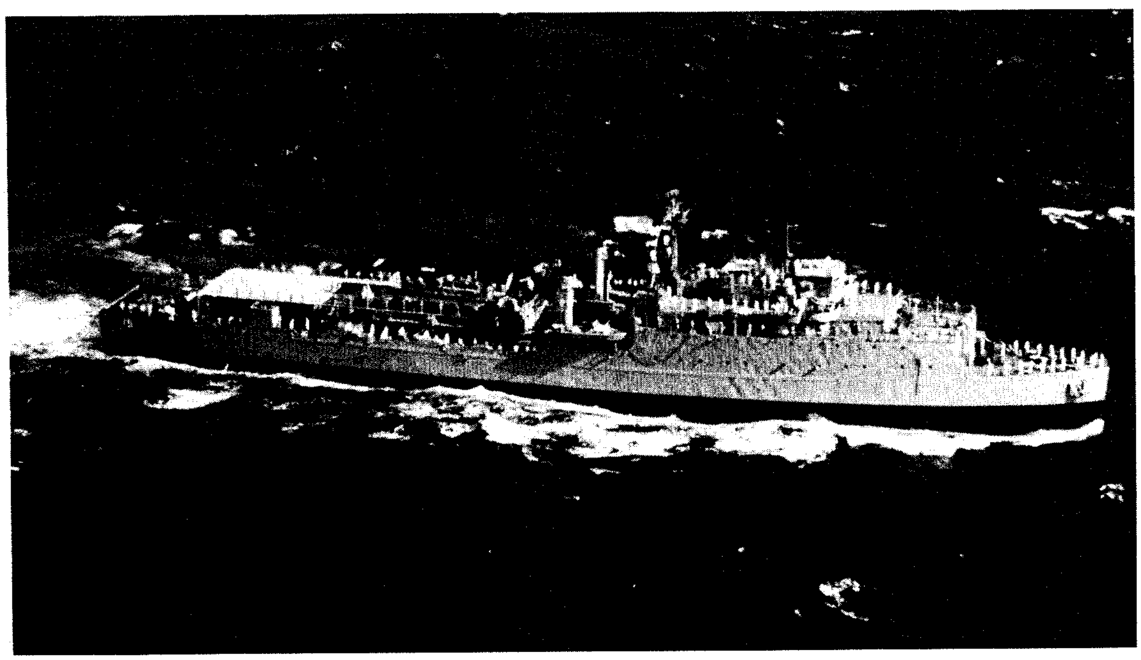

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Validation of fire models using large scale fire tests is important in the development of dependable and accurate fire models. Validation is especially critical as new phenomena are added to fire models. This report compares predictions from the Consolidated Fire Growth and Smoke Transport (CFAST) fire model to data from real scale fire tests conducted onboard ex-USS SHADWELL, the Navy's R&D Damage Control Platform. The phenomenon of particular interest in this validation is the conduction of heat in the vertical direction, which was recently added to CFAST in the ongoing effort to develop a fire model which is suitable to the Navy's needs. The SHADWELL tests chosen for validation purposes were part of the Internal Ship Conflagration Control (ISCC) program. The validation focused on four compartments which were vertically aligned. The temperatures of the four compartments and the decks between them were compared with model predictions. Predictions compared reasonably well with experimental results for the fire compartment (bottom compartment) as well as for the deck and compartment directly above it. The model overpredicted the temperatures of the compartments and decks not directly adjacent to the fire compartment. This should be a subject of further investigation.

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CONTENTS

VALIDATION OF FIRE/SMOKE SPREAD MODEL (CFAST) USING EX-USS SHADWELL INTERNAL SHIP CONFLAGRATION CONTROL (ISCC) FIRE TESTS

1.0 INTRODUCTION

Validation of fire models using large scale fire tests is important in the development of dependable and accurate fire models. The accuracy of model predictions is one of the major concerns expressed by ship operators. Validation is especially critical as new phenomena are added to the fire model. This report describes some features of the Consolidated Fire Growth and Smoke Transport (CFAST)[1] fire model [1] and compares its predictions to data from real scale fire tests conducted onboard ex-USS SHADWELL, the Navy's R&D Damage Control platform [2]. The phenomenon of particular interest in this validation is the conduction of heat in the vertical direction, which was recently added to CFAST in the ongoing effort to develop a fire model which is suitable to the Navy's needs. The ability to correctly account for conductive heat transfer through metal decks and bulkheads is especially important in the shipboard environment. Fire can spread as a result of rising temperatures in adjacent compartments that reach ignition levels even when no breach occurs in the initial fire compartment.

The SHADWELL tests chosen for the validation were conducted in the Internal Ship Conflagration Control (ISCC) program [3]. The ISCC program was initiated to provide guidance to the Fleet on the control of fire spread in both the vertical and horizontal directions. An additional objective was the development of new ship design criteria to address the devastation that occurred on the USS STARK as a result of missile-induced fires. There were numerous compartments involved in this test series, but this validation will focus on four compartments which were vertically aligned, i.e. four compartments stacked one on top of another. A version of the CFAST model, which incorporates vertical heat transfer through decks via conduction, was validated by comparing the experimental and model-predicted compartment gas temperatures as well as compartment deck temperatures.

2.0 SELECTION OF EXPERIMENTS

The ISCC test series on SHADWELL was conducted from 1989 to 1993 and included over a hundred experiments. The experiments that were used in this validation were chosen based on several criteria. Efforts were focused on the beginning of the series, before the

[1] - CFAST - Version 2.1 - executable dated 5 April 1994.

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cumulative effect of the fires on the integrity of the test compartments became too great. The tests had to be very similar in terms of experimental procedure, mass loss rate, and fuel nozzle type. Many of the early experiments which fit the above criteria had undergone statistical analysis by Desmatics, Inc. [4]. The analyses concluded that wind speed and direction had a significant effect on the temperatures produced by a fire. Since the analyses also identified anomalous experiments, only experiments which had undergone statistical analyses by Desmatics were used. To minimize the effect of wind, experiments which experienced low winds were chosen. The largest group of experiments which experienced low winds were those that had wind blowing from the south: dies_15, ins_3, ins_8, and ins_9. In addition, there were four experiments, conducted after the Desmatics study, which exhibited very good repeatability: ins_13, vent_1, vent_2, and vent_4. These complete the validation test set which will be referred to as: dies_15, ins_3 [5], ins_8 [6] and ins_9 [6], ins_13 [7], vent_1 [7], vent_2 [7], and vent_4 [7].

3.0 TEST CONFIGURATION

The ISCC experiments were conducted on the port wing wall of ex-USS SHADWELL (Fig. 1). The compartments which were of interest for this validation study were: Berthing 2 (the fire compartment), Ricer 2, CIC, and the Pilot House. All four compartments were located between frame 81 and frame 88. Berthing 2 and Ricer 2 were bounded by the well deck and hull. A deckhouse, which contained the CIC and Pilot House, was set on top of the main deck above Ricer 2.

3.1 Berthing 2:

The dimensions of Berthing 2 are shown in Fig. 2. The overhead and deck were both 0.95-cm-(0.375-in.)-thick steel. The forward (fwd), aft, and well deck bulkheads were 0.635-cm-(0.25-in.), 0.635-cm-(0.25-in.), and 1.27-cm-(0.5-in.)-thick steel, respectively. The hull was 1.59-cm-(0.625-in.)-thick steel. The lower portion of the hull, down 1.8 m (71 in.) from the overhead and defined by rectangle GHMN in Fig. 2, had seven openings. These openings, aligned horizontally, were all 1.13 m (44.5 in.) wide, with the following heights (from fwd to aft):

1. 0.98 m (38.5 in.)
2. 0.93 m (36.5 in.)
3. 0.90 m (35.5 in.)
4. 0.88 m (34.5 in.)
5. 0.85 m (33.5 in.)
6. 0.83 m (32.5 in.)
7. 0.80 m (31.5 in.)

There were two standard Navy archways (1.7 m x 0.7 m (5.5 ft x 2.2 ft)) which were open to the well deck and were 0.61 m (24 in.) above the deck of Berthing 2 (Fig. 1).

3.2 Ricer 2:

The dimensions for Ricer 2 are shown in Fig. 3. The overhead was 2.22-cm-(0.875-in.)-thick steel. The deck, fwd, aft, and well deck bulkheads were all 0.95-cm-(0.375-in.)-thick steel. The hull was 2.54-cm-(1.0-in.)-thick steel. In the fwd bulkhead there were two circular holes, both 2.86 cm (1.125 in.) in diameter, approximately 2.54 m (100 in.) above the deck. In the aft bulkhead, there was one circular hole, 2.86 cm (1.125 in.) in diameter, also 2.54 m (100 in.) above the deck. These three openings were partially blocked (50% to 75%) by instrumentation tubing and wiring. All the doors in this compartment were closed during the experiments. Some were warped, however, so they did not seal completely. In addition, as the series progressed, cracks developed in the deck because of the intense fire in the compartment below. The sizes of these openings around the doors and in the deck were estimated based on conversations with on-site personnel. The values used as input to the model will be discussed later in the section titled "Modeling Procedure."

3.3 CIC:

The dimensions for the CIC are shown in Fig. 4. The deck was 2.22-cm-(0.875-in.)-thick steel. The overhead and all bulkheads were 0.95-cm-(0.375 in.)-thick steel. There were four openings, 2.46 m (97 in.) above the deck, in the fwd bulkhead. Two of these openings were 1.91 cm (0.75 in.) in diameter. The other two were 2.86 cm (1.125 in.) in diameter. An additional opening in the aft bulkhead, 1.37 m (54 in.) above the deck, was 1.91 cm (0.75 in.) in diameter. The outboard bulkhead had an opening, 2.22 cm (0.875 in.) in diameter, located 1.23 m (48.5 in.) above the deck. The outboard bulkhead also had a mitered profile as shown in Fig. 5. The bottom edge of the CIC was not sealed where it contacted the main deck, so there were openings to weather all around the CIC perimeter. The total area of these openings was estimated based on conversations with on-site personnel and will be discussed later under "Modeling Procedure."

3.4 Pilot House:

The dimensions for the Pilot House are shown in Fig. 6. The deck, overhead, and bulkheads were all 0.95 cm-(0.375-in.)-thick steel. There was a 5.1 cm (2 in.) diameter hole in the deck.

4.0 EXPERIMENTAL PROCEDURE

Most of the experiments in the ISCC series were similar in procedure; however, differences did occur depending on the purpose of the particular experiment. The following description of the experimental procedure is limited to the eight experiments of interest in the series.

A post-flashover condition was created in Berthing 2 using three diesel spray fires. Initially, there was a pre-burn period of 170 to 190 sec (183 sec average) during which time heptane was burned in three fuel pans. These fuel pans, each 1.2 x 1.2 m (4 x 4 ft), were placed 5.1 cm (2 in.) above the deck. The fwd, mid, and aft pans were centered 1.5 m (5 ft) from the well deck bulkhead and 1.8 m (6 ft), 4.3 m (14 ft), and 6.7 m (22 ft) from the fwd bulkhead, respectively. The initial fuel charge to the center fuel pan was 26.5 liters (7 gal). The other two held 15.1 liters (4 gal) each. All three pans were ignited simultaneously and the pool fires were allowed to die down before the diesel fuel was sprayed across the hot pans. A flat fan spray nozzle (Bete Fog Nozzle, Inc. Model FF 073145) was positioned over each pan, approximately 17 cm (6.5 in.) above the deck. The total fuel flow, split evenly to the three nozzles, varied from 14.4 lpm (3.8 gpm) to 18.2 lpm (4.8 gpm) with an average of 16.4 lpm (4.3 gpm). The entire burn time was 20 minutes, including the preburn period. There were differences among some of the eight experiments after the 20 minute burn period. Consequently, only the data collected during these 20 minutes was used for validation purposes.

5.0 INSTRUMENTATION

The instruments discussed in this section are limited to those used for validation purposes.

5.1 Berthing 2:

There were two vertical thermocouple strings, each containing five thermocouple (Fig. 7). One string was located near the fwd bulkhead (thermocouples 13-17) and the other was located near the compartment center at frame 86 (thermocouples 18-22). The thermocouples were located 46 cm (18 in.), 91 cm (36 in.), 137 cm (54 in.), 183 cm (72 in.), and 229 cm (90 in.) above the deck.

5.2 Ricer 2:

There were two vertical thermocouple strings (Fig. 8). One string was located in the fwd portion of the compartment at frame 82 and the other was located in the aft portion at frame 86. Both the fwd (thermocouples 126-129) and aft (thermocouples 130-134) strings contained thermocouples located at 91 cm (36 in.), 137 cm (54 in.), 183 cm (72 in.), and 229 cm (90 in.) above the deck. The aft string had an additional thermocouple located 46 cm (18 in.) above the deck. Thermocouple 125, which was located 46 cm (18 in.) above the deck on the fwd string, was not available for all of the experiments and, therefore, was not used. The number and location of deck thermocouples varied depending on the experiment. There was only one for dies_15 (thermocouple 148). Since the purpose of the ins_* experiments was to test the effectiveness of insulation in preventing fire spread, more deck thermocouples were installed. During ins_3, there were seven thermocouples which measured Ricer 2 deck temperature in areas where the Berthing 2 overhead was bare steel (thermocouples 61, 62, 64, 65, 66, 67, and 69). In the remaining experiments, only thermocouples 62, 64, and 67 were used to measure unprotected deck temperatures. Thermocouple 147 (labeled 148 in dies_15) was also used to measure the deck temperature in these experiments. The location of this particular thermocouple in ins_3, however, is unclear and therefore was not used in this validation.

5.3 CIC:

There were two vertical thermocouple strings in this compartment (Fig. 9). The fwd string (thermocouples 91-96) was located at frame 83 and the aft string (thermocouples 97-102) was located at frame 86. Each string contained six thermocouples, 20 cm (8 in.), 46 cm (18 in.), 91 cm (36 in.), 137 cm (54 in.), 183 cm (72 in.), and 229 cm (90 in.) above the deck. There was one thermocouple (thermocouple 104) which measured the deck temperature in this compartment.

5.4 Pilot House:

There were only two thermocouples on each of the two thermocouple strings (thermocouples 85-88) in the Pilot House (Fig. 10). They were 56 cm (22 in.) and 112 cm (44 in.) above the deck. The deck temperature was measured using just one thermocouple (thermocouple 90).

6.0 MODELING PROCEDURE

The quality of a model validation depends upon the accuracy of the model input, i.e. the model input must reflect the experimental conditions as closely as possible. There are instances, however, when input to the model had to be estimated because either the information about the experimental set-up was unknown or the model was unable to handle certain configurations. The instances where estimates had to be made will be discussed in following sections, defined by this criteria.

6.1 Unknown Experimental Set-up Information:

The size of the vent openings, both between decks and to weather, must be included in the model input. These were not always known precisely. Cracks formed in the deck of Ricer 2 as a result of the intense fire in the compartment below. These cracks were periodically repaired, but there was no record kept as to their size during any given experiment. Based on conversations with personnel who were on-site during these experiments, the area of the opening represented by cracks between Berthing 2 and Ricer 2 was estimated to be 19 sq cm (3 sq in.).

The sizes of the openings to weather around the warped doors in Ricer 2 were also transient and undocumented. There were two estimates obtained from on-site personnel. One person estimated a total area of 50 sq cm (8 sq in.). Another person suggested that the total area of the openings was equivalent to an 11 cm (4.5 in.) opening around the bottom half of one door's perimeter. The second estimate, because it was the largest, was used as model input.

The model was also run with no opening in the deck between Berthing 2 and Ricer 2 and with no vents to weather in Ricer 2. The results from these predictions are shown in the plots (which will be described later in the RESULTS section) as "Model - Limit." This should provide the reader with an appreciation for the effect that the above estimates can have on the model results. The smallest (i.e. zero) and largest estimates for the vent size openings were used with the intent that the two resulting predictions would bracket the model output which would have resulted from the use of the actual opening sizes, if known.

As previously mentioned, there were openings between the lower edge of the CIC and the main deck. Again, there were two estimates obtained from on-site personnel for this parameter. The first estimate was that the maximum leak area was 290 sq cm (45 sq in.). The second estimate was that the average clearance between the lower edge of the CIC and the main deck was 0.6 cm (0.25 in.). The second estimate, which resulted in the largest area estimate, was chosen to use as model input. In this particular case, the choice was irrelevant. The model gave the same results regardless of which size opening was chosen. The model also gave the same result when the opening around the bottom edge was removed from the input file altogether. Consequently, a limiting case for this vent size is not shown.

The final estimate which had to be made was the mass loss rate of fuel during the pre-burn period. As previously mentioned, a total of 57 liters (15 gal) was charged to the fuel pans and ignited. The diesel spray was started after the pool fires started to die down. The actual mass loss rate of the heptane during this period was not measured. Consequently, the mass loss rate was estimated to be 0.097 kg/sec. This translates to a total of 26.3 liters (7 gal) burned during the pre-burn period.

6.2 Model Limitations:

The model assumes that each compartment is a rectangle. Since none of the compartments were rectangles, their dimensions had to be adjusted for input to the model. For all compartments, the actual compartment length was used (the distance between frames 81 and 88). Effective widths were calculated so that the surface area of each overhead was the same as that in the actual compartment. The heights were then adjusted, if necessary, so that the compartment volumes were the same as the actual compartment volumes. This meant that the wall surface areas of the compartments, as inputted, were different than those in the actual compartments. The wall surface area is used by the model to calculate the total heat transfer to and from the walls.

The model only accepts one thickness for all four walls in each compartment. Both Berthing 2 and Ricer 2 had walls of differing thicknesses. A weighted average based on actual surface area was used as input to the model for these compartments. The model uses the wall thickness to calculate conductive heat transfer through the walls.

7.0 RESULTS AND DISCUSSION

Before the results of the validation are discussed in detail, it is important to review exactly what is being compared. CFAST is a zone model. It divides the compartments into two layers - an upper and a lower. Each layer is assumed to be of uniform temperature and composition. Experimentally, however, temperatures are measured at a limited number of discrete locations. Inherent in the process of averaging these measurements to define the overall characteristics of each layer is the danger that this average does not represent reality at all. This is of particular concern when the thermocouples show there is extreme non-uniformity in the temperatures between different parts of the compartment at the same height.

The figures to be discussed in this section will show the experimental results as well as the model results from three different predictions. "Model - Vers 1" refers to the output obtained from using a previous version of CFAST which did not incorporate vertical heat transfer through decks via conduction. "Model - Vers 2" was obtained using the same input files as "Model - Vers 1", in the enhanced version of CFAST which does incorporate this phenomenon . "Model - Limit" refers to results obtained from using version 2 of the model with an input file which does not include the cracks in Ricer 2 deck or the openings around the doors in Ricer 2.

In most cases, the experimental results given in the figures are an average of the eight experiments. The figures will also show error bars which represent one standard deviation in the data obtained from the eight different experiments. This will illustrate the degree of repeatability obtained from these experiments.

The model results given in the figures for "Model - Vers 2" and "Model - Limit" are an average of eight predictions. The eight predictions were obtained by using the actual fuel mass loss rate of each of the eight experiments. The error bars, representing one standard deviation in these results, show the scatter in temperature which would be expected from the variation in the fuel load among the experiments. The results from version 1 of the model were obtained from one run of the model using the average fuel mass loss rate from the eight experiments and do not include error bars.

7.1 Berthing 2:

Berthing 2 was the fire compartment. Both the model and the experimental data results show that almost the entire compartment was in the upper layer during the experiments (Fig. 11). The experimental interface was derived from the vertical temperature readings using the method described in reference 8. With the exception of the transition time between the pre-burn and diesel spray fires, the small error bars show there was very good agreement among the experiments. The fact that this transition occurred at slightly different times during each of the experiments probably accounts for the large scatter in interface height around this time. There was little difference between the model version 1 or version 2 predictions. The "Model - Limit" predictions were also essentially identical to the other two model results and thus were not shown. The effect of variation in fuel mass loss rate on the model version 2 predictions was very small. The error bars, although plotted, are covered by the symbols in the plot. There was excellent agreement between the model-predicted and experimentally-determined interface heights.

The experimentally-determined interface height was always below the lowest thermocouple in the strings except during the small transition period between the pre-burn and the diesel spray fire. Therefore, for each experiment, all of the thermocouples were averaged to obtain the upper layer temperature in Berthing 2. The average compartment temperatures for each experiment were then averaged to obtain the experimental results shown in Fig. 12. The error bars reflect substantial deviation in the average compartment temperature among the experiments. Again, the largest error bars were in the transition period between the pre-burn and diesel spray fires.

Most of the thermocouples in the aft string did not work correctly during dies_15 and ins_13, so the average shown in Fig. 12 does not include data from these two experiments. The average temperature of the fwd string for these two experiments, however, was comparable to the average of the fwd string for the other six (Fig. 13). It is, therefore, reasonable to assume that the average temperatures shown in Fig. 12 are representative of all eight experiments.

The temperature predictions from version 2 of the model were higher than those from version 1. This is because in version 1 the model assumes the energy is conducting through the fire compartment overhead into the ambient environment which remains at a constant temperature. In version 2, the heat is conducting into Ricer 2 which heats up as energy is accumulated in the compartment. Since the temperature difference between the two compartments is less, less heat is transferred from Berthing 2 and, consequently, the temperature in Berthing 2 is higher. Again, running the model with an input file from the "Model - Limit" scenario made no difference in the results and thus is not shown on the plot. The model-predicted temperatures were always within the experimental error bars.

There was a substantial difference in the average temperatures of the fwd thermocouples versus the thermocouples on the aft string. Figure 14 shows there was a 200 to 300 degree celsius difference. The thermocouples on the aft string also exhibited much more scatter than those on the fwd string. This figure also shows the error bars associated with the temperature variation due to the different fuel mass loss rates among the experiments. Only a small part of the observed differences among the experiments can be attributed to this variable.

7.2 Ricer 2 Deck:

Since there were seven thermocouples used to measure the temperature of the deck between Berthing 2 and Ricer 2 during ins_3, as opposed to the maximum of three during the other experiments, ins_3 was chosen to provide the best estimate of the deck temperature. There was extreme non-uniformity among these thermocouples, as can be observed by the large error bars in Fig. 15. The actual fuel mass loss rate for ins_3 was used as model input for the Ricer 2 deck predictions. The results from the enhanced version of the model (Vers 2) almost always fall within the error bars of the experimental data. Version 1 of the model does not properly account for the heat conducted through the Ricer 2 deck. This version of the model assumes that all of the heat conducted through the Berthing 2 overhead is lost to the ambient environment, i.e. none of the heat enters Ricer 2. Consequently, version 1 of the model predicts that the deck will remain at ambient (room) temperature throughout the experiment. Clearly, the predictions from the enhanced model (Vers 2) are much more realistic.

There were three deck thermocouples (62, 64, and 67) which were common to all experiments except dies_15. The temperatures of these three thermocouples only, were averaged to obtain a deck temperature for all the experiments except for dies_15. Figure 16 shows the deck temperature obtained from averaging these averages from all the experiments except for dies_15 and ins_3 and compares it to the average from ins_3. The excellent agreement between the two justifies the use of ins_3 as a representative of the others for the Ricer 2 deck temperature. There was very good reproducibility in this particular measurement among ins_13, ins_8, ins_9, vent_1, vent_2, and vent_4, as shown by the very small error bars. Although not shown, these three thermocouples also revealed that the deck temperature was extremely non-uniform during all of the experiments. Figure 17 shows that similar results were obtained regardless of the presence or absence of openings in the deck between Ricer 2 and Berthing 2 or around Ricer 2 doors.

7.3 Ricer 2:

In the limit of no openings in the deck or around the doors, the model predicted that the entire compartment remained in the lower layer (Fig. 18). A small upper layer formed when these openings were assumed to exist. It will be shown later that the model predicted that this layer consisted of the combustion products from Berthing 2. In both cases the interface height was above the highest thermocouple in both strings. It did not make sense to calculate the interface height from the experimental data because of the inconsistent stratification revealed by the two thermocouple strings. The hottest temperatures were near the bottom of the aft string and near the top of the fwd string. Therefore, for each experiment, all the thermocouples were averaged to determine the temperature of the lower layer in Ricer 2. These average temperatures from the individual experiments were then averaged and compared with model predictions in Fig. 19. The error bars on the experimental data show that there was much better agreement among the experiments than there was in the case of the Berthing 2 temperatures. The experimental error bars are even smaller than those on the model predictions which resulted from variations in the fuel mass loss rate. The model (Vers 2) and experiment compare reasonably well in the beginning and end of the experiment, but are different by about 50 degrees celsius in the middle portion. The model version (Vers 1), which does not incorporate vertical heat transfer through decks via conduction, predicts that the compartment above the fire compartment will remain at ambient temperature. Again, clearly the use of the enhanced version (Vers 2) of the model results in a much more realistic prediction.

The two thermocouple strings in Ricer 2 will be designated in the following discussions as fwd and aft, referring to their location within the compartment. The thermocouples on the fwd string were averaged together and the thermocouples on the aft string were averaged together for each experiment. These average temperatures from the individual experiments were then averaged and compared to model predictions in Fig. 20. The error bars on the experimental data show the variation among the experiments, not the variation among the thermocouples on each of the strings. Even though the thermocouples on each of the strings read very close to each other (within 30 degrees celsius), the difference between the average of the fwd and the average of the aft strings reached about 70 degrees celsius toward the end of the experiments. The thermocouples on the aft string all read temperatures higher than any on the fwd string. On the aft thermocouple string, the hottest temperatures were observed near the bottom. On the fwd string, the cooler temperatures were near the bottom. This suggests there was probably some type of circulation pattern within the compartment. There was definitely no consistent stratification of any kind.

Figure 21 shows the comparison between the model (Vers 2) run with and without the openings in Ricer 2 deck and around the doors. The temperature is lower when these openings are present. Heat is entering Ricer 2 from Berthing 2 via mass transfer through the cracks in the deck, but more is being lost to weather through the openings around the doors.

The model predicts that the hot combustion products enter Ricer 2 at the bottom of the compartment, travel through the lower layer without mixing, and accumulate in an upper layer. This is evident in Fig. 18 which shows that a hot layer of other than negligible depth doesn't exist unless there is mass transfer into the compartment. Figure 22 shows that the model predicts that the lower layer remains at 21 vol% oxygen concentration while the upper layer's oxygen concentration decreases with time. The oxygen concentration levels out at around 6 vol%, which is the same concentration as the model-predicted Berthing 2 concentration. Experimentally, this type of phenomenon was not observed. Gas sampling for oxygen, carbon dioxide, and carbon monoxide was done at two locations. These were in a vertical line, 0.79 m (31 in.) and 2.29 m (90 in.) from the deck, 0.20 m (8 in.) aft of the fwd bulkhead and 2.34 m (92 in.) outboard of the well deck bulkhead. The oxygen concentration in Ricer 2 decreased as a result of dilution with combustion products coming through the cracks from Berthing 2. This decrease, obtained by averaging the readings from these two sample points, varied from experiment to experiment depending most likely on the size of the cracks in the deck. By the end of the experiments, the total decrease in oxygen concentration ranged from about 1 vol% to 3 vol% and increased sequentially in the order that the experiments were done. This also suggests that the cracks in the deck got bigger as the series progressed. Even though both of the sampling points were located in the lower layer as defined by the model, the readings from neither one remained at 21 vol% as predicted by the model. In fact, for dies_15, ins_8, ins_9, and vent_1, the measured oxygen concentration was about the same for both sample points, suggesting that the combustion products were somewhat evenly dispersed throughout the compartment. For ins_3, vent_2, and vent_4, the readings from the upper sample point were either larger or smaller than the readings from the lower sample point. These observations suggest that there was no consistent pattern of gas species concentration within Ricer 2 among these seven experiments. There were no gas analyses available for ins_13. It is clear that regardless of how the combustion products were dispersed within the compartment, whether evenly or unevenly, they definitely did not rise to the top of the compartment completely unaffecting the lower layer as predicted by the model. One well mixed layer, rather than two separate layers, is probably a more accurate depiction of this compartment.

It is interesting to note that the model-predicted average oxygen concentration, calculated by volume-averaging, was approximately 19 vol% at the end of the experiment. This is within the range of 18 to 20 vol% seen experimentally, which suggests that the estimate of the crack size was close to the actual size.

7.4 CIC Deck:

There was only one thermocouple measuring the temperature of the CIC deck. The readings from this one thermocouple were averaged over all eight experiments and compared to model predictions in Fig. 23. At the end of the experiment, the average deck temperature was about 150 degrees celsius, whereas the model-predicted (Vers 2) deck temperature was over 300 degrees. The largest overprediction by the model (Vers 2) of the temperature in Ricer 2 (the compartment directly below this deck) was about 50 degrees celsius (Fig. 19). It is reasonable to expect the model to overpredict the temperature in the deck or compartment above one for which it has already overpredicted the air temperature, since the heat is traveling upward and outward. The relative magnitude of the overprediction in the CIC deck suggests, however, that there is another explanation for this large deviation from the experimental data. It is possible that one thermocouple is not reading a representative temperature for the entire deck. It is unlikely, however, that the actual average deck temperature is twice as high as this one thermocouple.

The model-predicted (Vers 2) and experimentally-determined CIC deck temperatures did not agree as well as those in the case of the Ricer 2 deck. It is interesting to note that the CIC deck was twice as thick as the deck between Berthing 2 and Ricer 2. Another difference between the Ricer 2 deck and CIC deck was the presence of raised scuttles on the CIC deck (Fig. 24). The model does not allow for this type of configuration. Consequently, the model input did not include the raised scuttles even though their presence may affect the results. The final difference between the Ricer 2 and CIC decks was the fact that the Ricer 2 deck and Berthing 2 overhead had the same area, whereas the CIC deck had a smaller area than the overhead in Ricer 2.

There was very good reproducibilty in the experimental data, as evidenced by the small error bars (Fig. 23). They were, in fact, much smaller than those on the model predictions, generated by the variation in fuel mass loss rate. As always, lack of incorporating the algorithm which properly accounts for the conductive heat transfer through decks, resulted in predictions that the deck would remain at ambient temperature throughout the experiment.

Predictions from the model as a result of using the "Model - Limit" input file, i.e. assuming there were no openings in Ricer 2 deck or around Ricer 2 doors, were slightly higher than those obtained when these openings were assumed to be present (Fig. 25). This is to be expected since the "Model - Limit" case resulted in a warmer Ricer 2 compartment temperature (Fig. 21).

7.5 CIC:

The model predicted the interface height would remain very close to the overhead throughout the experiment. Experimentally, all twelve thermocouples read very close to each other. Therefore, these twelve readings were averaged to obtain the compartment temperature for each experiment. These averages were then averaged and compared to the model predictions in Fig. 26. Again, the model (Vers 2) overpredicted the temperature, 120 versus 50 degrees celsius at the end of the experiment. This is not surprising since the CIC deck temperature was overpredicted. Reproducibility in the experimental data was excellent. Version 1 of the model predicted that the CIC would remain at ambient temperature. This is consistent with previous results. Predictions obtained from the model when the openings in Ricer 2 deck and around Ricer 2 doors were assumed to be absent were slightly higher than those obtained when they were assumed to be present (Fig. 27). This is also consistent with previous results.

The model (Vers 2) predicted the entire CIC was essentially in the lower layer with only a very small upper layer adjacent to the CIC overhead. The model also predicted that this upper layer remained cool relative to the lower layer (Fig. 28). If, in reality, the gas immediately adjacent to the overhead was close to the same temperature as the lower layer, the model would have underpredicted the convective heat transfer to the overhead from the upper layer. Again, as with Ricer 2, it appears that treating this compartment as one layer instead of two would be more realistic. It is interesting to note that the model did not predict a cool upper layer temperature relative to the lower layer in Ricer 2 (Fig. 29). This is because the hot combustion gases from Berthing 2 were deposited into the upper layer. Without this mass transfer, the upper layer would have remained cool relative to the lower layer.

7.6 Pilot House Deck:

There was one thermocouple which read the temperature of the Pilot House deck. As with the CIC deck, the readings from this thermocouple were averaged over all eight experiments and compared to model predictions (Fig. 30). The model (Vers 2) overpredicted this deck temperature. The experimentally-measured increase above ambient was about five degrees celsius, whereas the model predicted it would be around 20 degrees celsius. Version 1 of the model predicted the deck would never increase above ambient at all. Using the enhanced version of CFAST and assuming there were no openings in Ricer 2 deck or around Ricer 2 doors resulted in model predictions even higher (Fig. 31). This is to be expected since the heat that wasn't lost to weather from Ricer 2 made its way up to the Pilot House.

7.7 Pilot House:

The model predicted the entire Pilot House compartment was essentially in the lower layer. During the experiments all four thermocouples read very close to each other. Therefore, all four thermocouples were averaged from each of the eight experiments. These averages were then averaged to obtain the experimentally-determined temperature which was compared to the model predictions in Fig. 32. Experimentally, the temperature increased only a few degrees above ambient, whereas the model (Vers 2) predicted a slightly larger increase of more than five degrees celsius. The overprediction by the model is fairly insignificant in both the Pilot House compartment and its deck since, at these locations, the increase above ambient is quite small for both the predictions and experiments. Version 1 of the model predicted that the Pilot House would remain at ambient temperature. Figure 33 shows that the model would predict a very slightly higher temperature if there were no openings in Ricer 2 deck and around Ricer 2 doors. Although too small to be considered significant, it is consistent with previous results.

8.0 CONCLUSION

Prior to incorporation of the algorithm into CFAST which properly accounts for vertical heat transfer by conduction, the model predicted that the temperatures in the compartments and decks above a fire compartment would not increase above ambient. After incorporating the algorithm, the model predicted much more realistic results. These predictions compared reasonably well with experimental results for the fire compartment as well as for the deck and compartment directly above it. The model overpredicted the temperatures of the compartments and decks not directly adjacent to the fire compartment. This should be a subject of further investigation. It is uncertain what role the assumption of two layers in this particular scenario plays in the overprediction of the CIC and its deck temperatures. Investigation into the differences between the Ricer 2 and CIC decks (thickness, presense of raised hatches, and unequal heat transfer surface areas) may also provide reasons for the discrepancies. Replacing the two layer assumption with one well mixed layer for this particular scenario may or may not resolve the temperature overprediction. It should, however, provide a more accurate prediction for both species concentration in the compartment and convective heat transfer to the overhead.

9.0 ACKNOWLEDGMENTS

Special thanks to John Hoover of NRL for providing advice and critical comments regarding this report. Additional thanks to Fred Williams, Arthur Durkin, and CDR John Farley of NRL, Joe Scheffey and Terry Toomey of Hughes Associates, Inc., Henry Whitesel and John Overby of NSWC, Carderock Division, and Brad Havlovick of Havlovick Engineering Services, Inc. for their time and patience in providing information about the ISCC test program.

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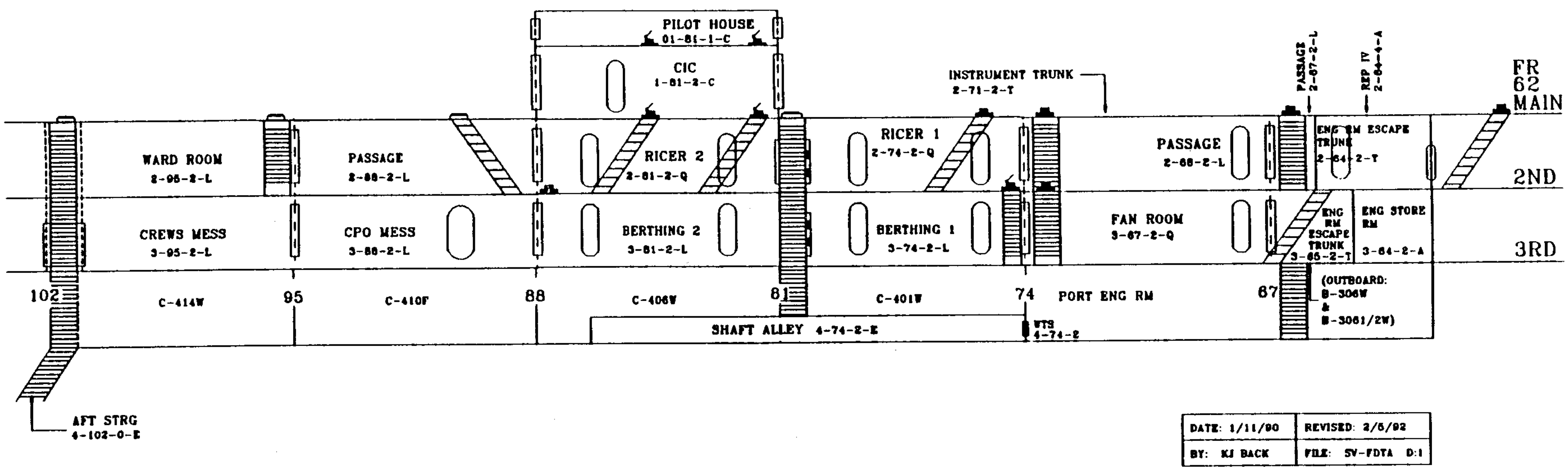
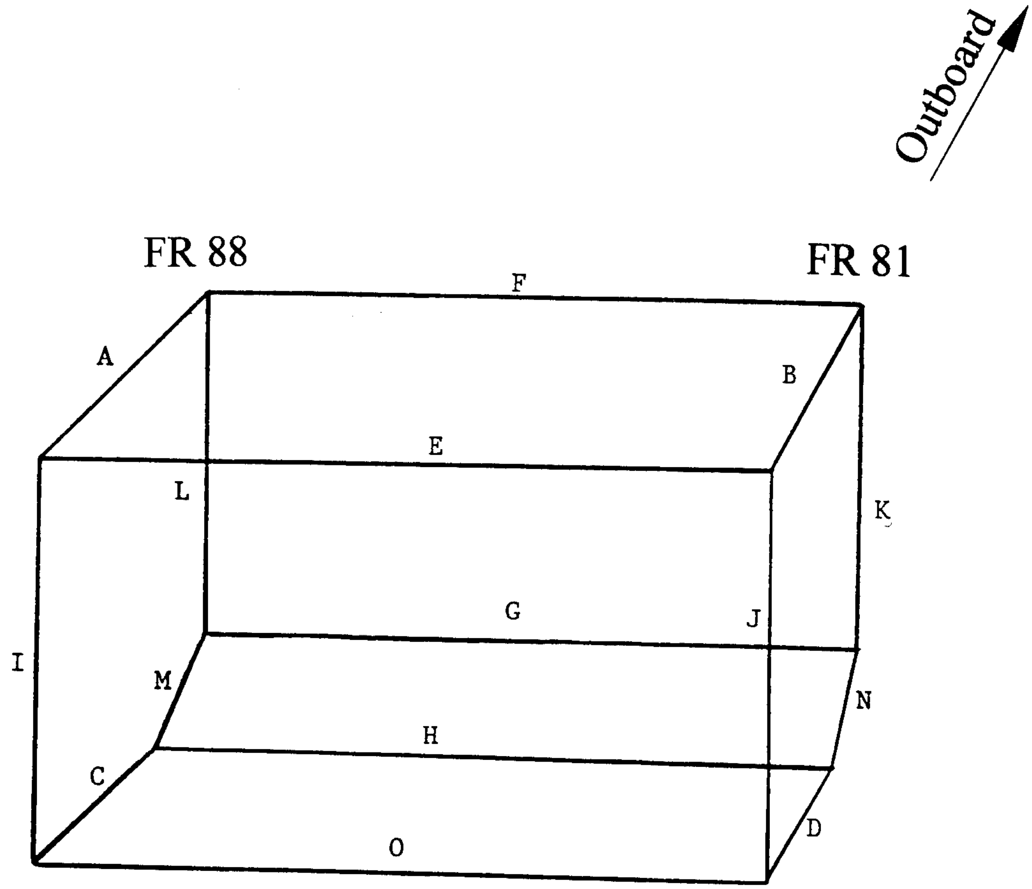


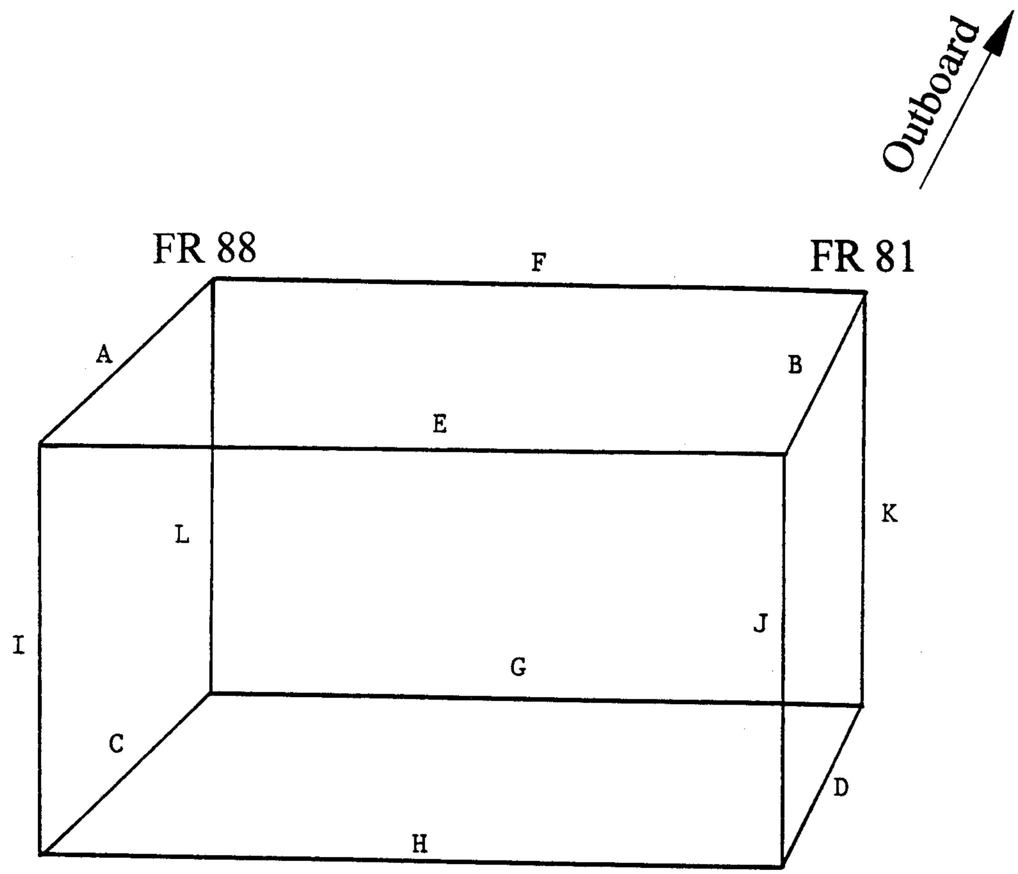
Fig. 1 - ex-SHADWELL, section view, port wing wall ISCC test area

(Figure from reference 6)



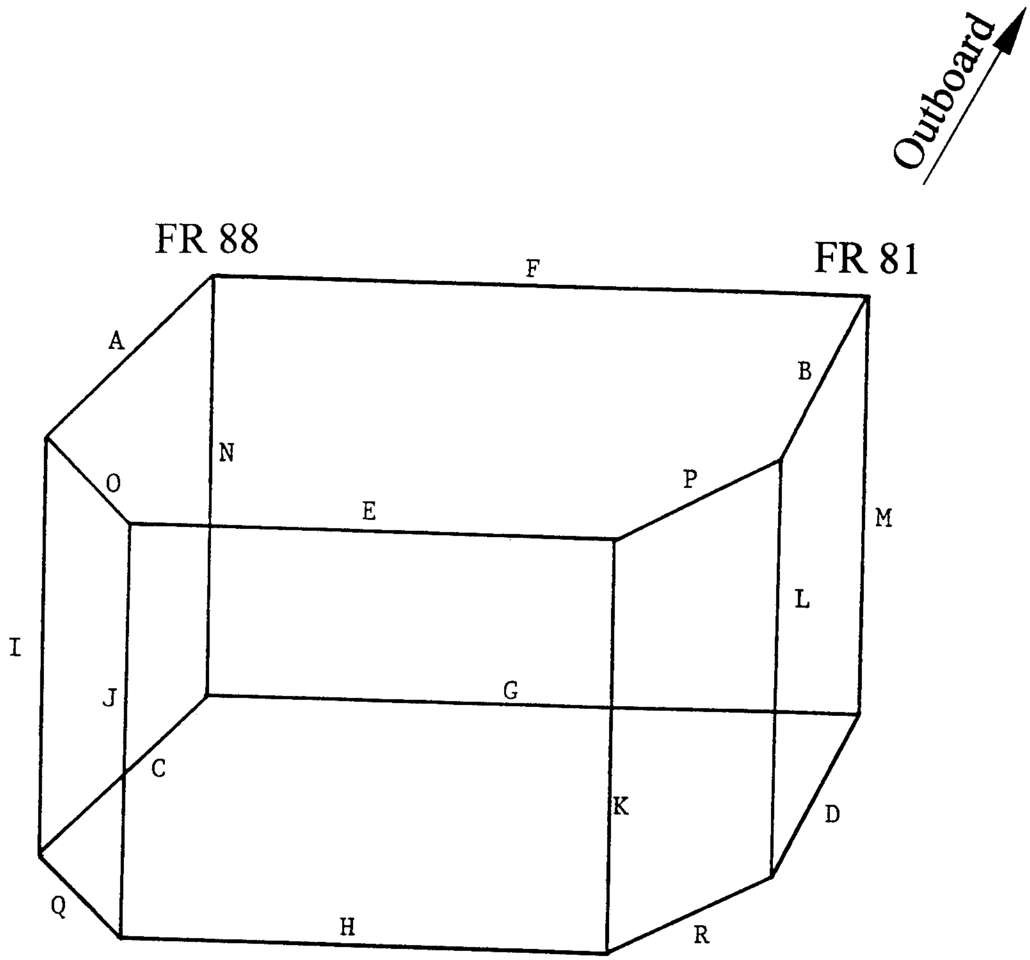
A:	3.9 m (153 in.)
B:	4.1 m (163 in.)
C:	3.3 m (129 in.)
D:	3.4 m (135 in.)
E:	8.6 m (337 in.)
F:	8.5 m (334 in.)
G:	8.5 m (335 in.)
H:	8.5 m (335 in.)
I:	2.6 m (101 in.)
J:	2.6 m (101 in.)
K:	1.8 m (71 in.)
L:	1.8 m (71 in.)
M:	0.8 m (32 in.)
N:	1.0 m (39 in.)
O:	8.5 m (335 in.)

Fig. 2 - Berthing 2 Dimensions



A:	3.9 m (154 in.)	G:	8.5 m (335 in.)
B:	4.1 m (163 in.)	H:	8.6 m (337 in.)
C:	3.9 m (153 in.)	I:	2.6 m (102 in.)
D:	4.1 m (163 in.)	J:	2.6 m (102 in.)
E:	8.6 m (337 in.)	K:	2.6 m (102 in.)
F:	8.5 m (334 in.)	L:	2.6 m (102 in.)

Fig. 3 - Ricer 2 Dimensions



A: 2.2 m (86 in.)	J: 2.6 m (102 in.)
B: 2.2 m (86 in.)	K: 2.6 m (102 in.)
C: 2.2 m (85 in.)	L: 2.6 m (102 in.)
D: 2.2 m (85 in.)	M: 2.6 m (102 in.)
E: 6.0 m (235 in.)	N: 2.6 m (102 in.)
F: 8.5 m (336 in.)	O: 1.4 m (57 in.)
G: 8.5 m (336 in.)	P: 1.4 m (57 in.)
H: 6.0 m (235 in.)	Q: 1.4 m (57 in.)
I: 2.6 m (102 in.)	R: 1.4 m (57 in.)

Fig. 4 - CIC Dimensions

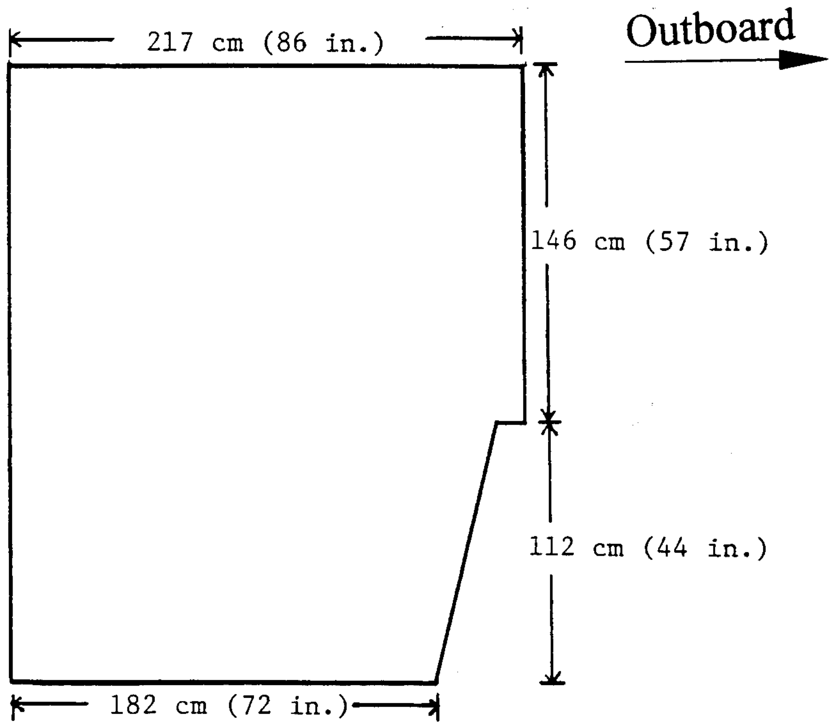
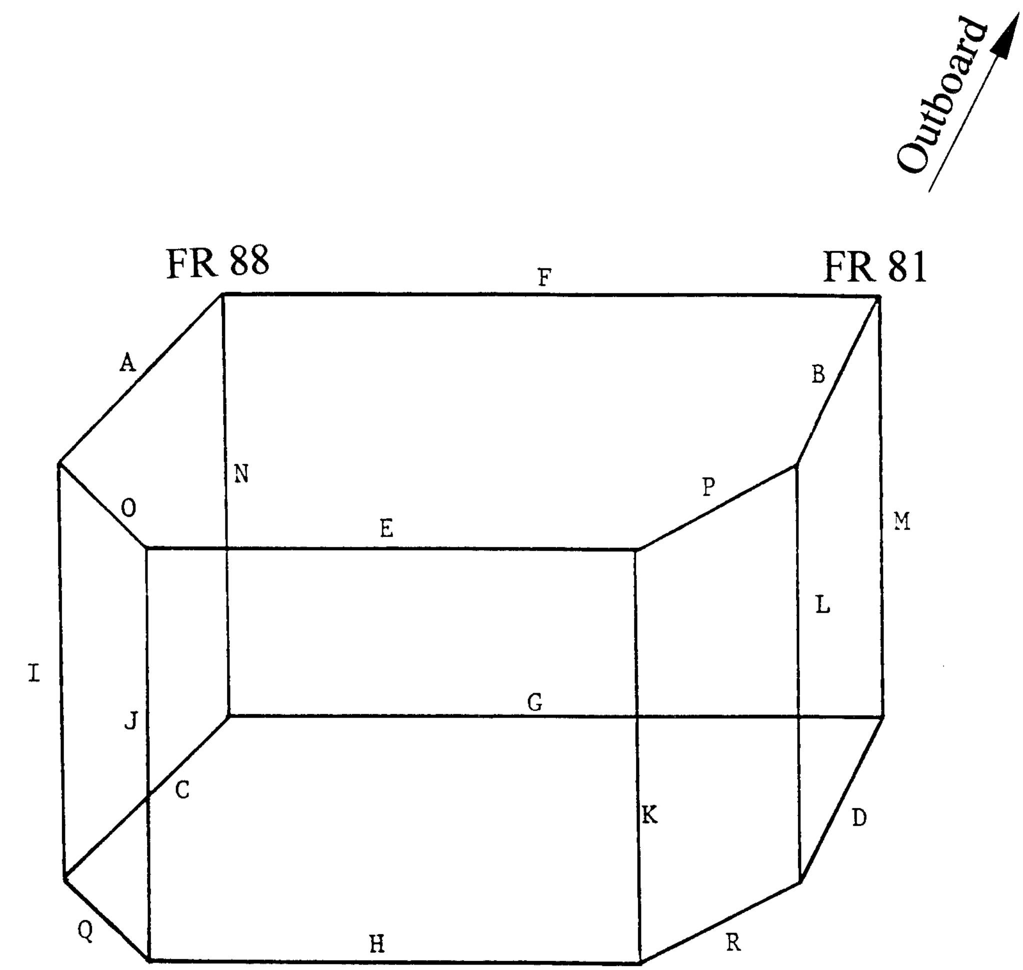


Fig. 5 - CIC Outboard Bulkhead Profile



A:	2.2 m (86 in.)
B:	2.2 m (86 in.)
C:	2.2 m (86 in.)
D:	2.2 m (86 in.)
E:	6.0 m (235 in.)
F:	8.5 m (336 in.)
G:	8.5 m (336 in.)
H:	6.0 m (235 in.)
I:	1.1 m (43 in.)
J:	1.1 m (43 in.)
K:	1.1 m (43 in.)
L:	1.1 m (43 in.)
M:	1.1 m (43 in.)
N:	1.1 m (43 in.)
O:	1.4 m (57 in.)
P:	1.4 m (57 in.)
Q:	1.4 m (57 in.)
R:	1.4 m (57 in.)

Fig. 6 - Pilot House Dimensions

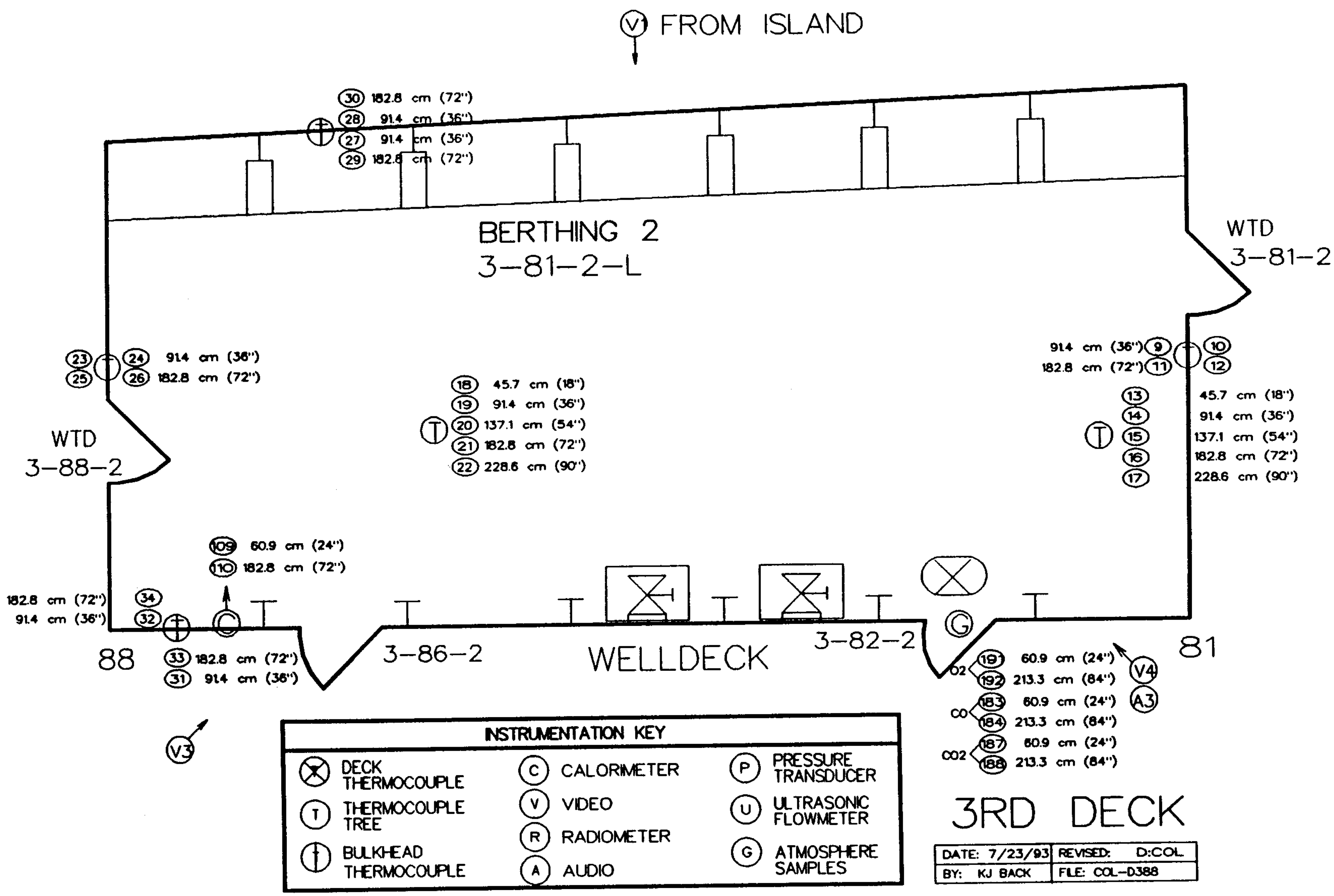
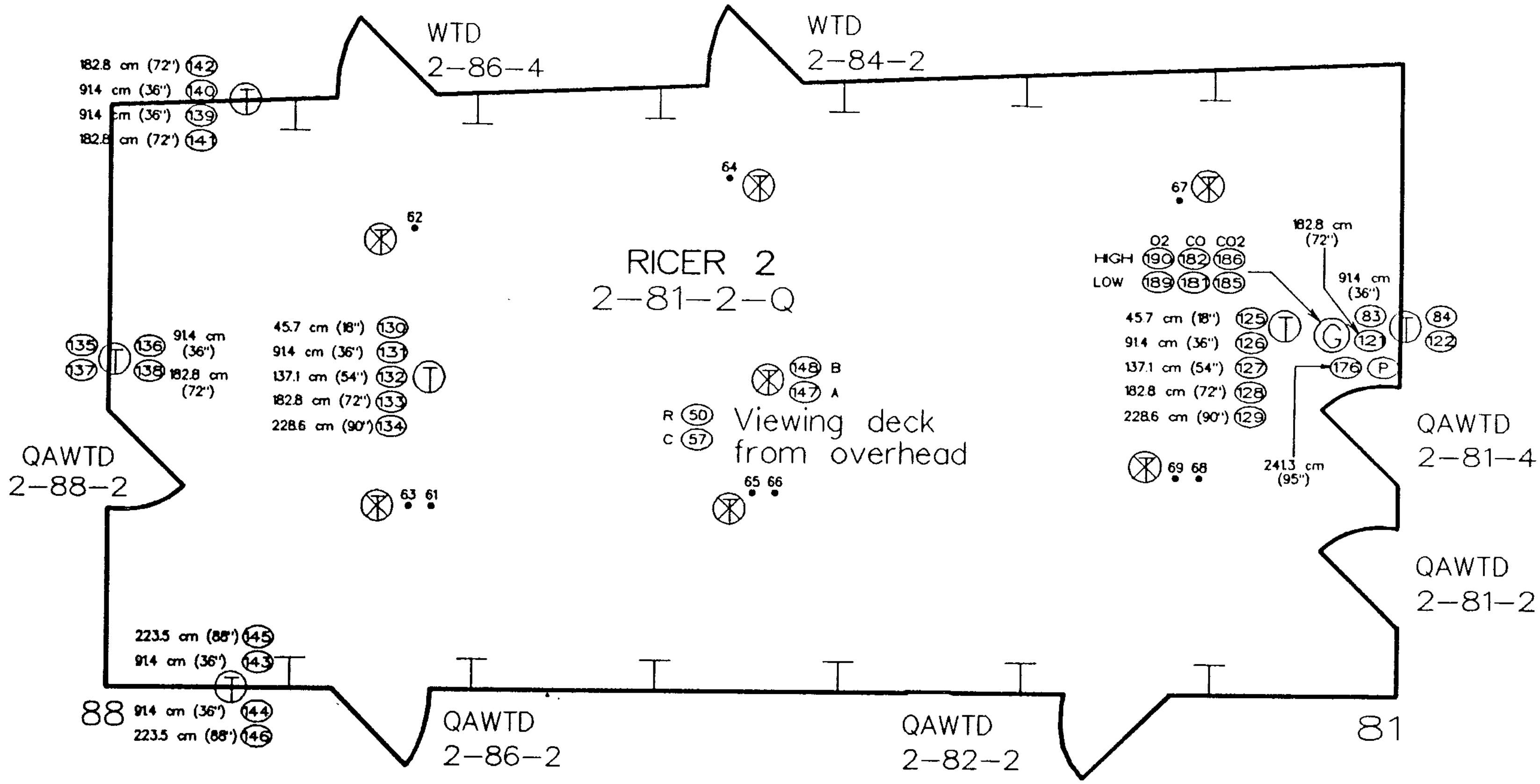


Fig. 7 - Third Deck Plan View, Berthing 2

(Figure from reference 9)



Note: Key - see Fig. 7

2ND DECK

DATE: 7/23/93	REVISED: 1/94 D: COL
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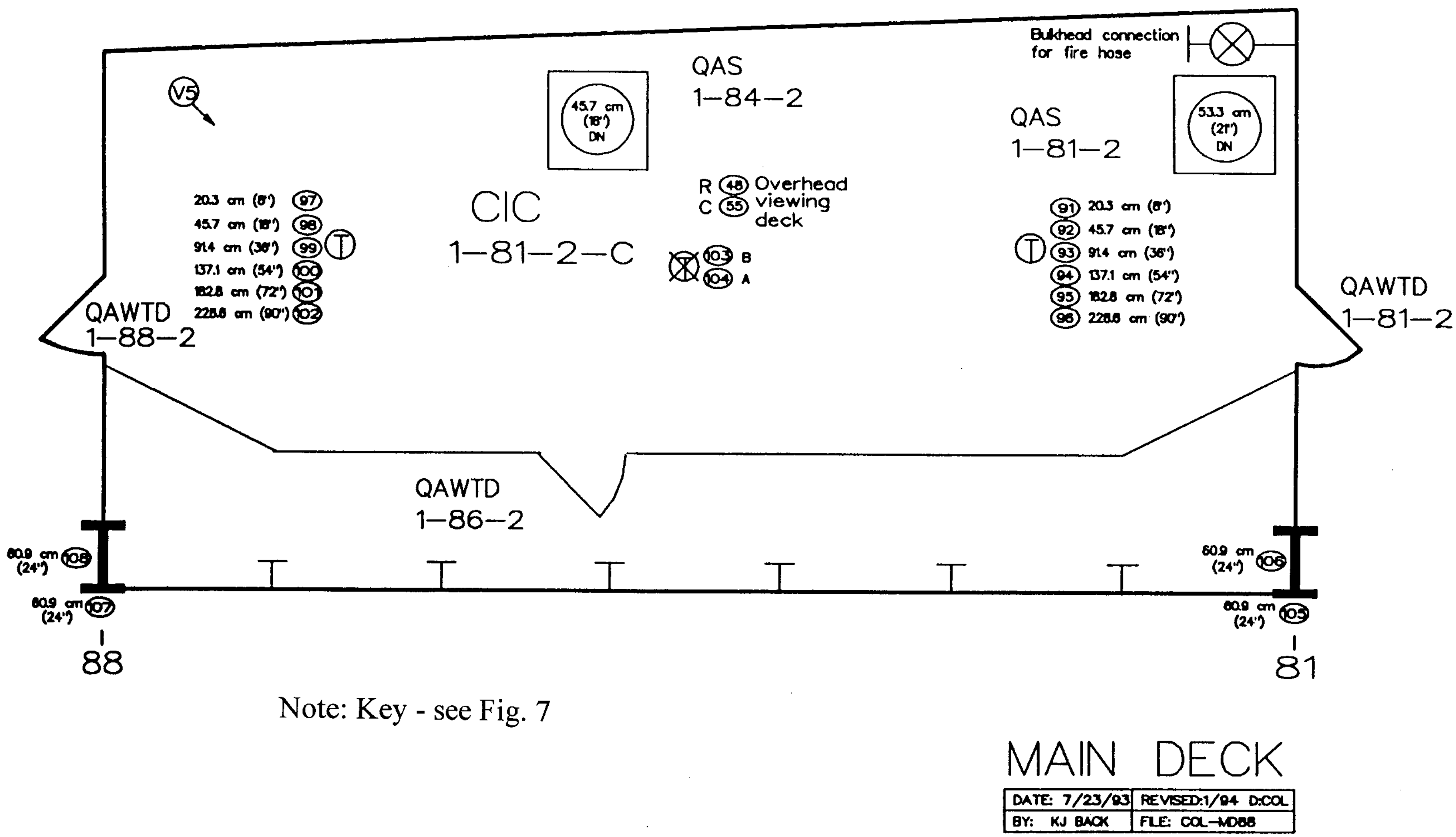
Fig. 8 - Second Deck Plan View, Ricer 2

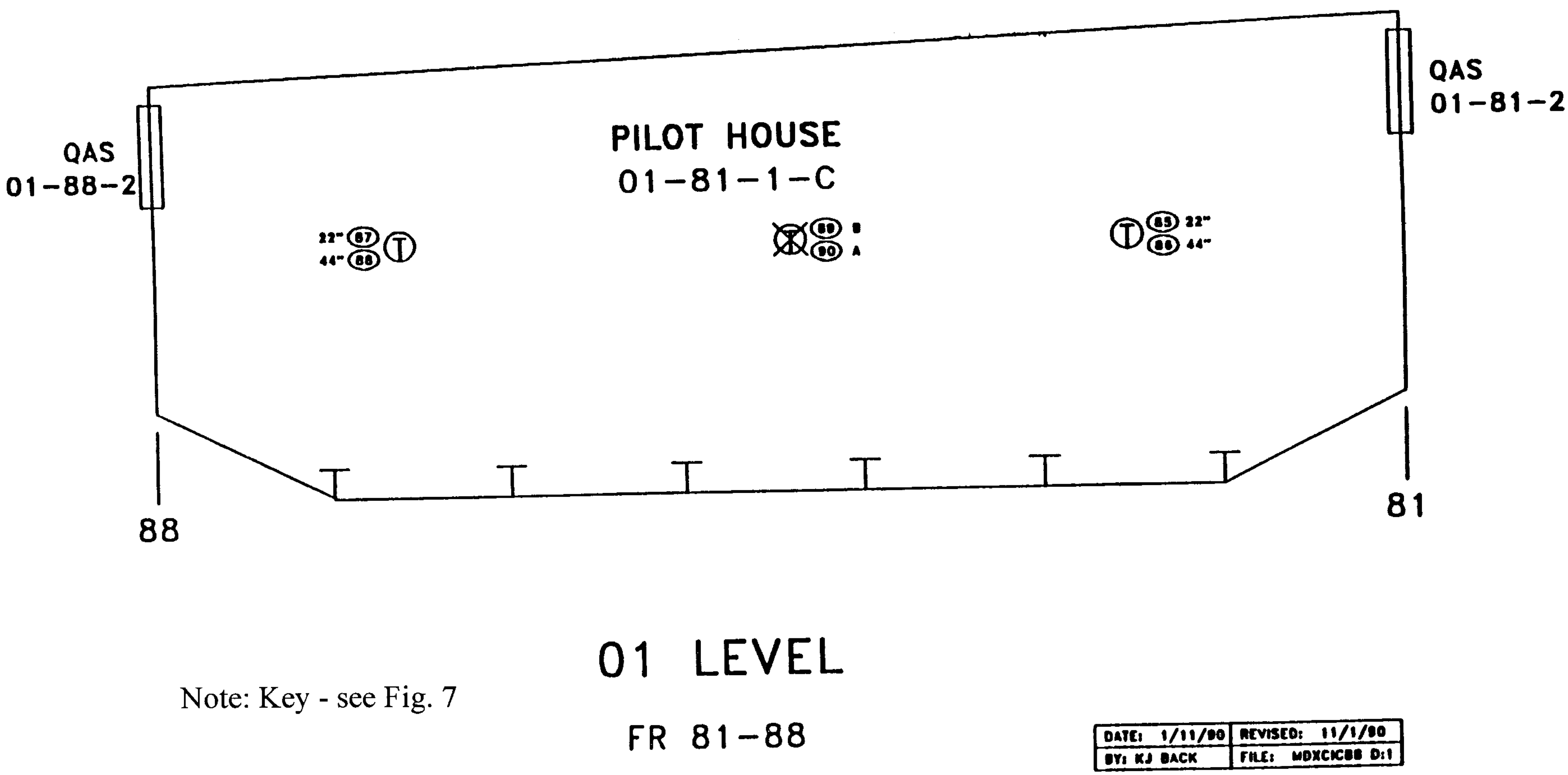
(Figure from reference 9)



Note: Key - see Fig. 7

Fig. 9 - Main Deck Plan View, CIC

(Figure from reference 9)



Note: Key - see Fig. 7

Fig. 10 - 01 Level Plan View, Pilot House

(Figure from reference 10)

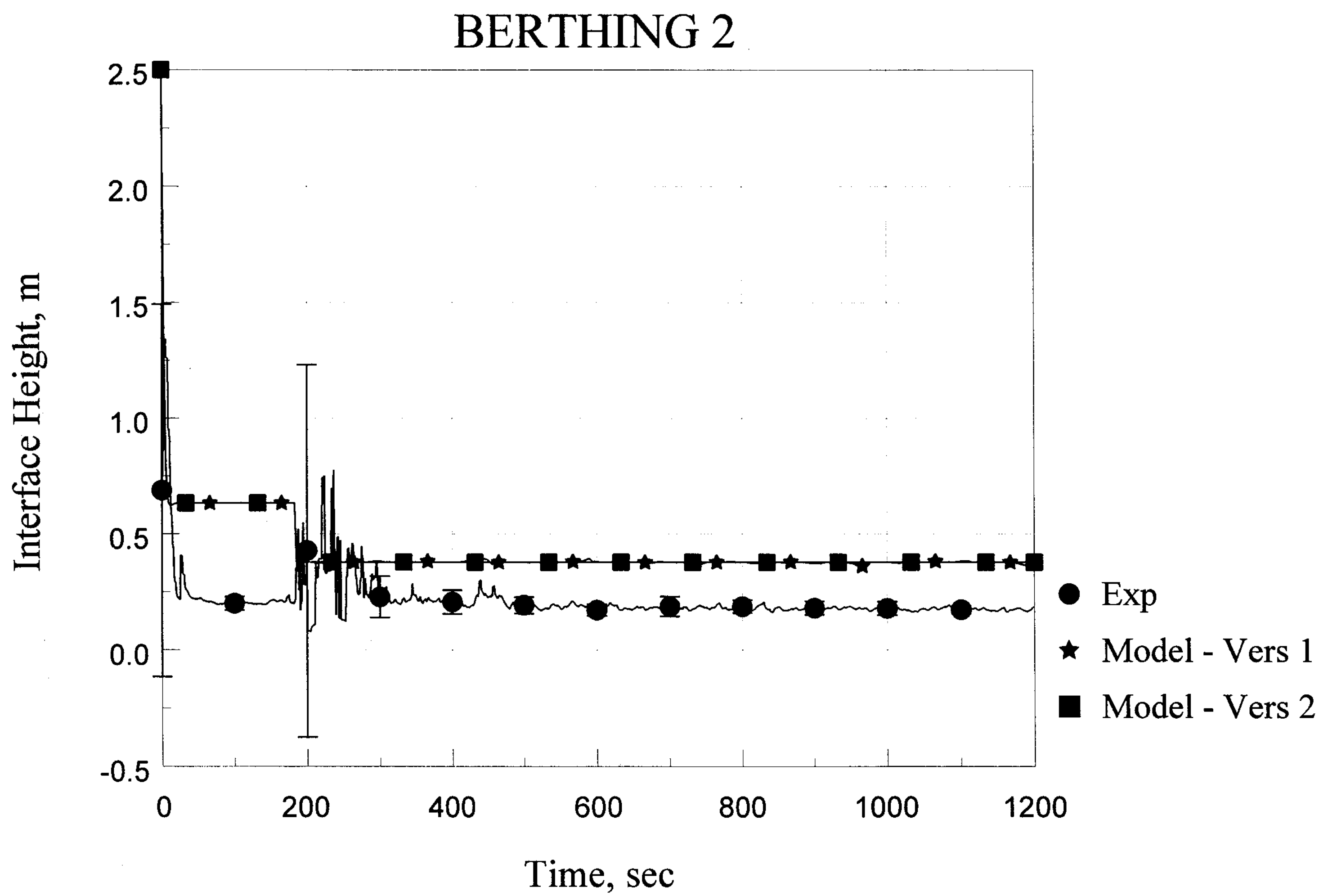


Fig. 11 - Model-Predicted Versus Experimentally-Determined Interface Height in Berthing 2

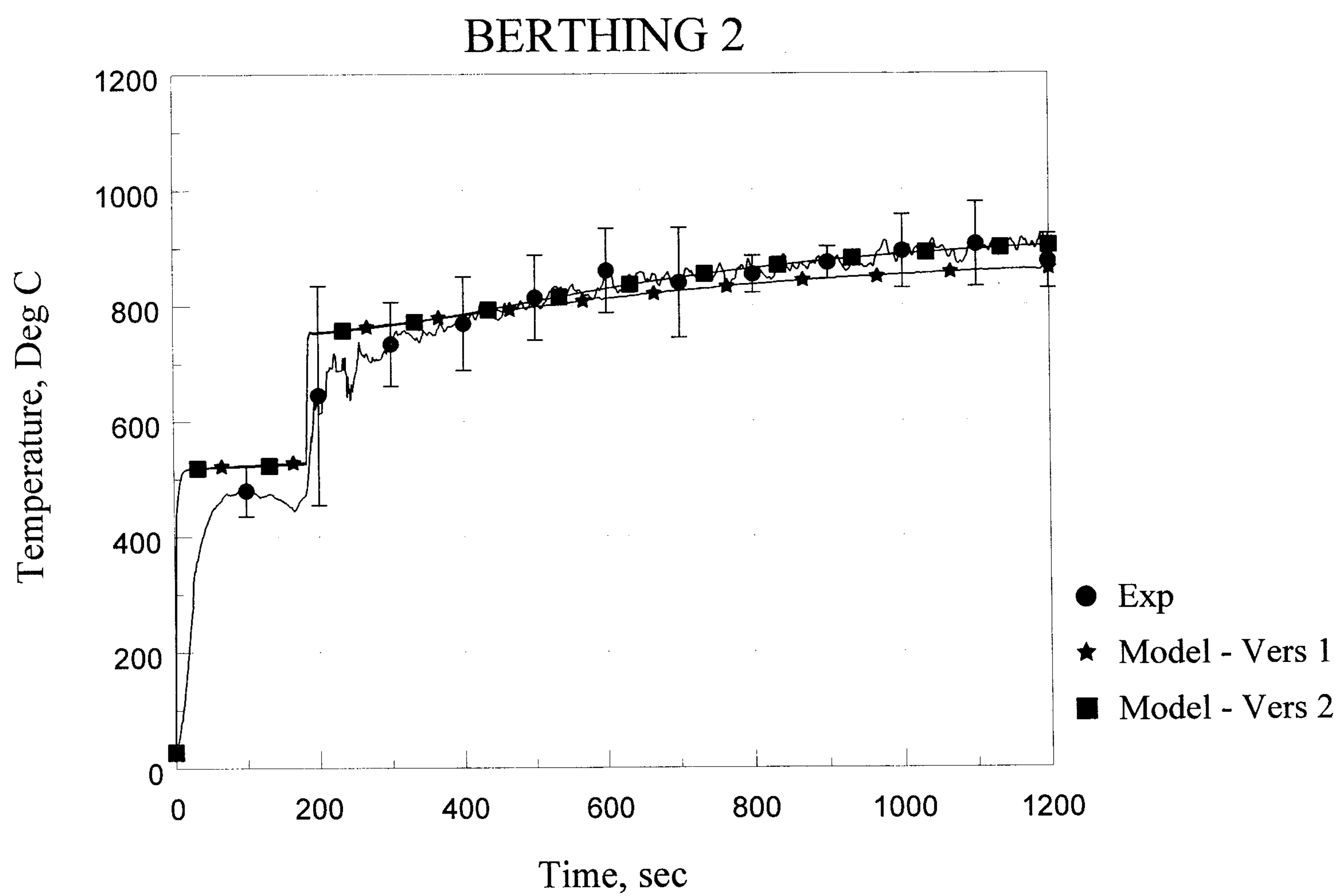


Fig. 12 - Model-Predicted Versus Experimentally-Determined Upper Layer Temperature in Berthing 2

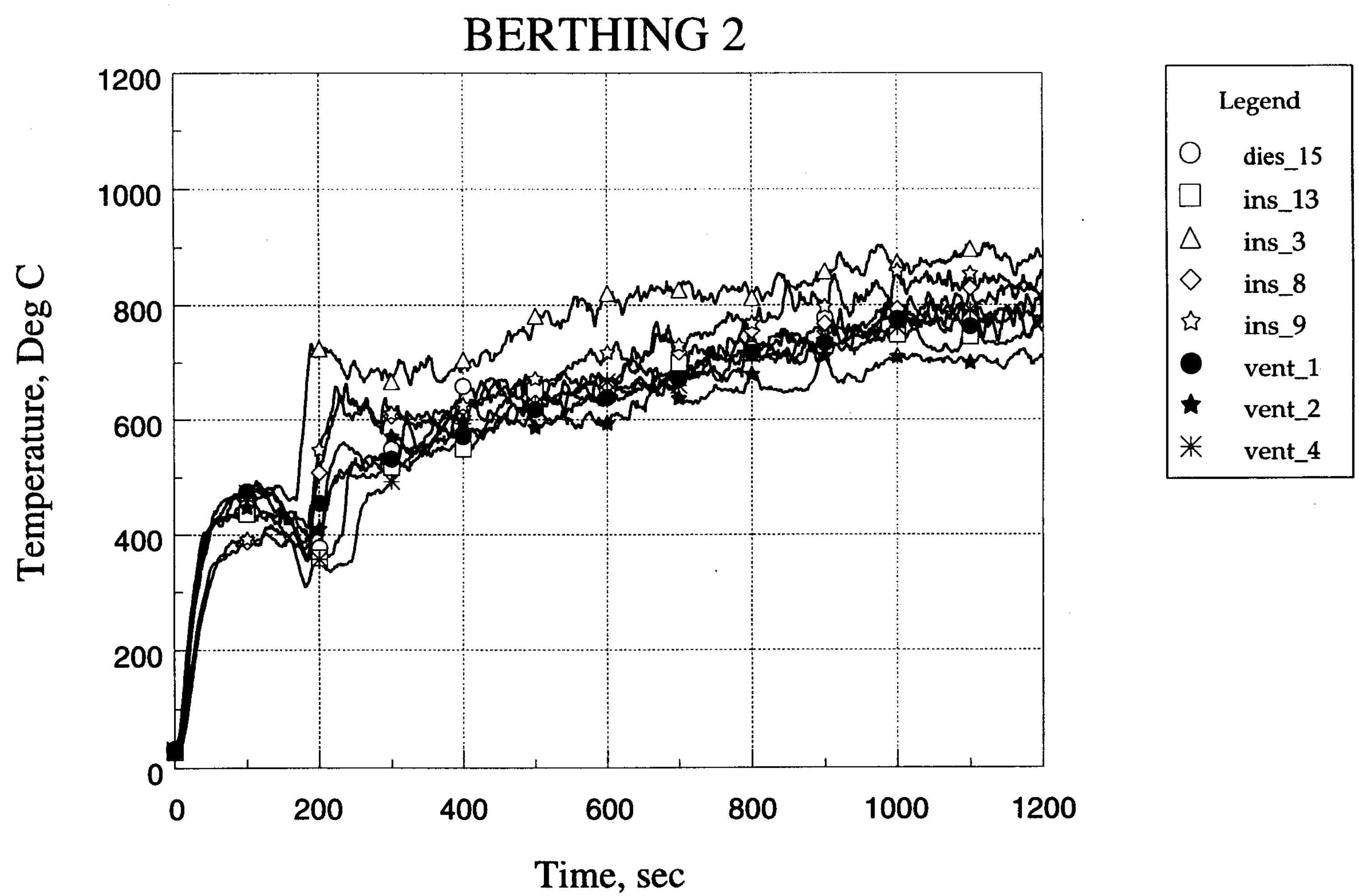


Fig. 13 - Average of Fwd Thermocouple String In Berthing 2 for Individual Experiments

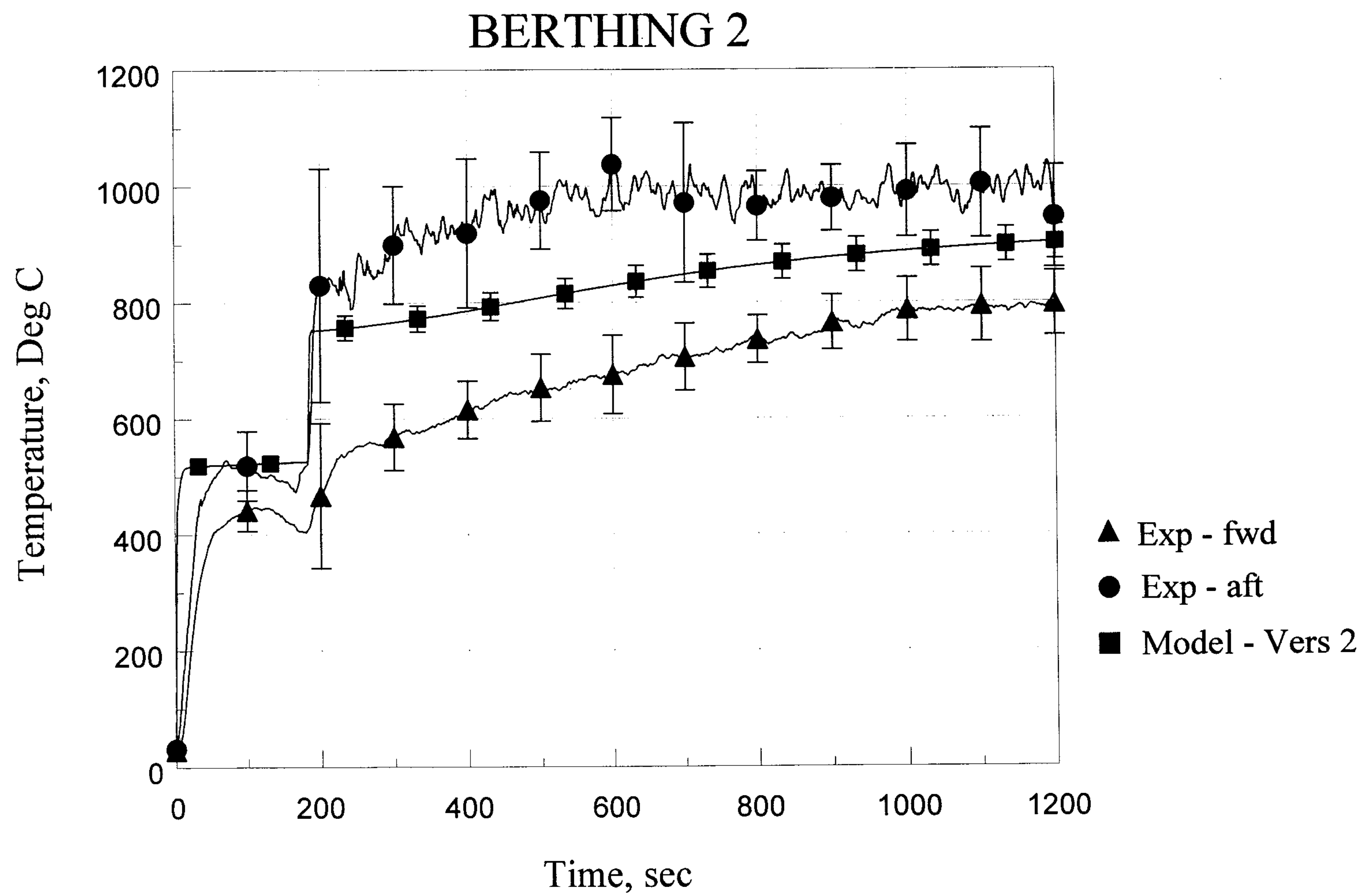


Fig. 14 - Experimentally-Determined Fwd and Aft Versus Model-Predicted Temperatures in Berthing 2

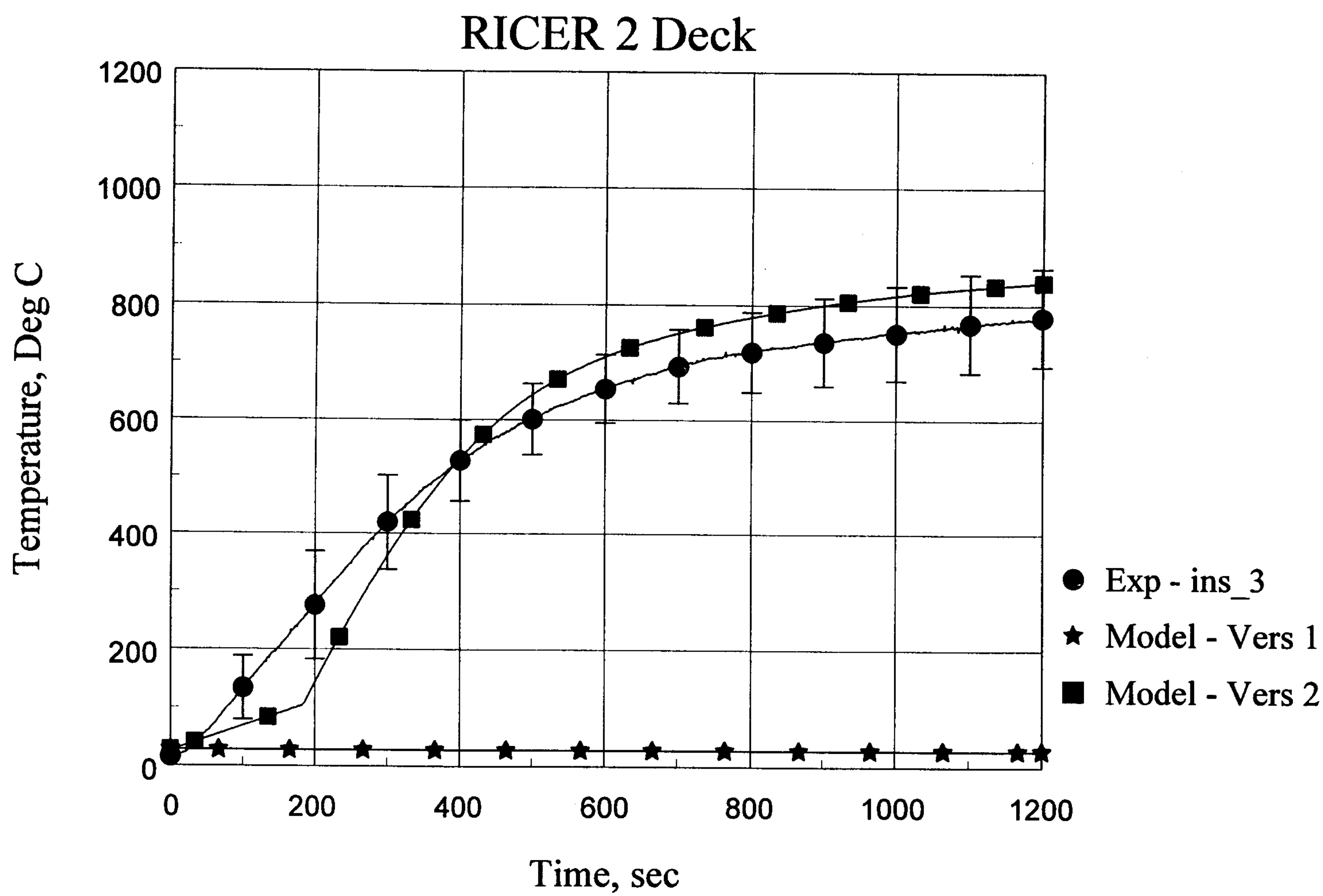


Fig. 15 - Model-Predicted Versus Experimentally-Determined Ricer 2 Deck Temperature for INS_3

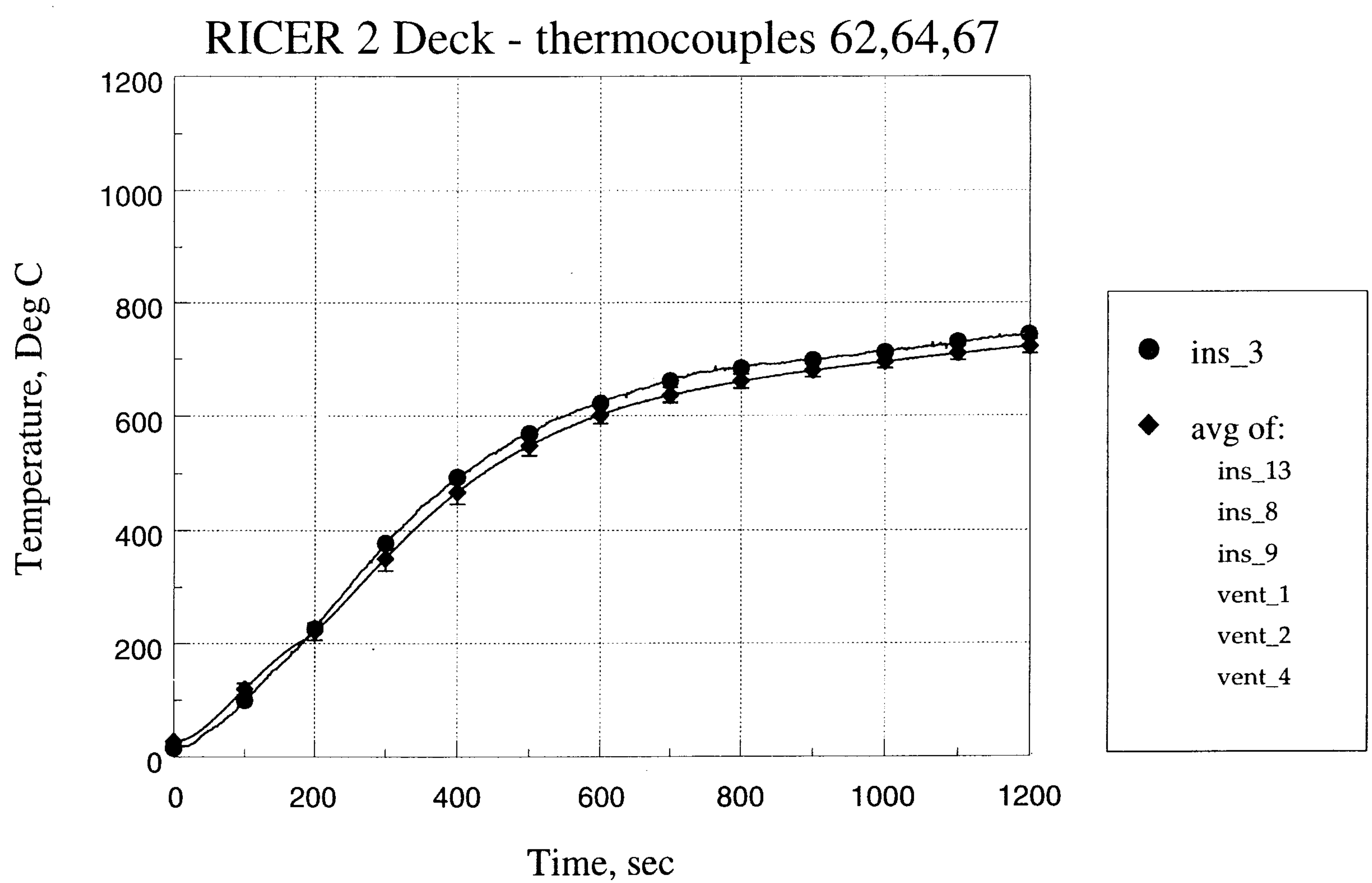


Fig. 16 - Comparison Between Ins_3 Deck Temperature and Average of Other Experiments

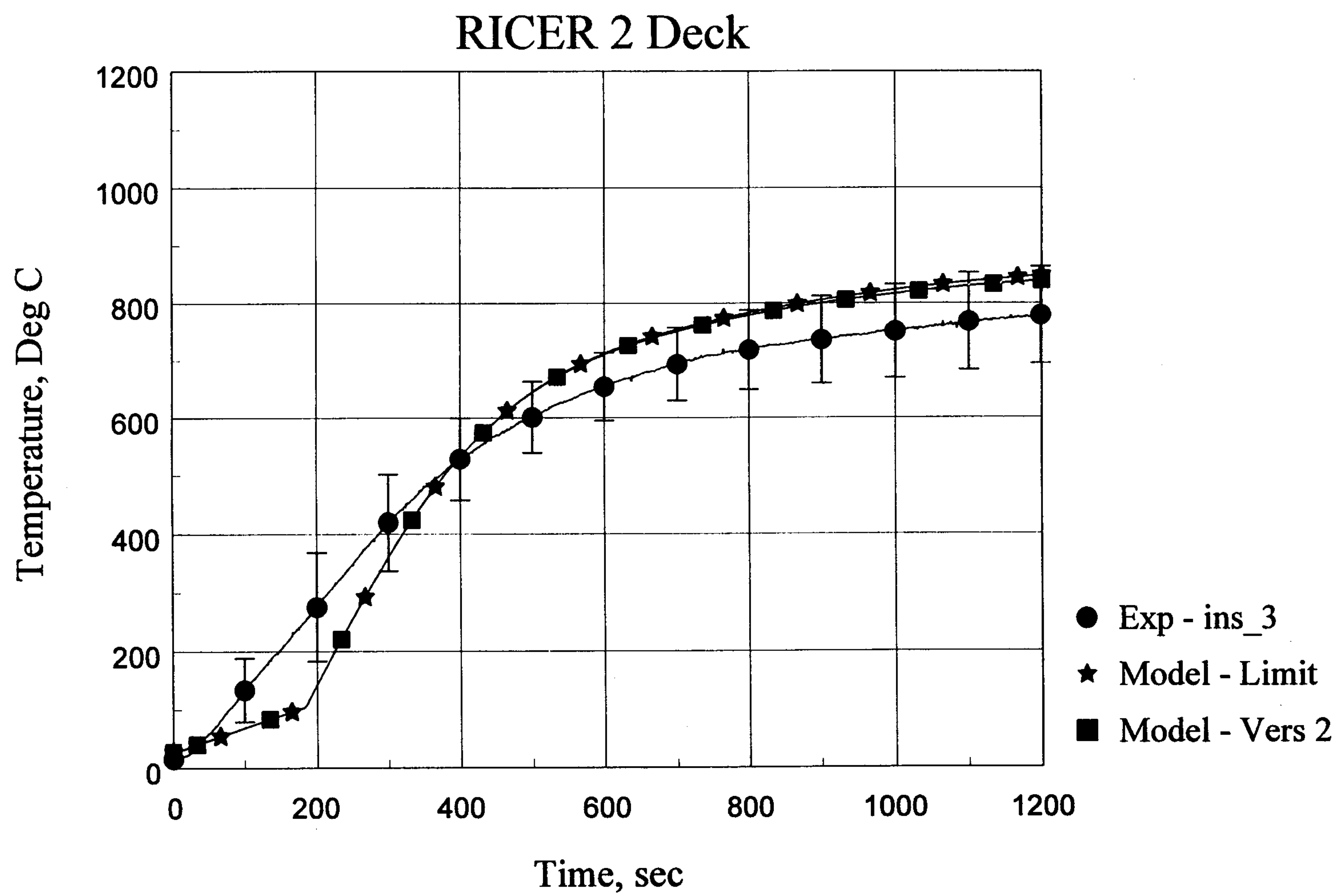


Fig. 17 - Comparison of Model-Predicted Ricer 2 Deck Temperature With and Without Openings in Ricer 2 Deck and Around Ricer 2 Doors

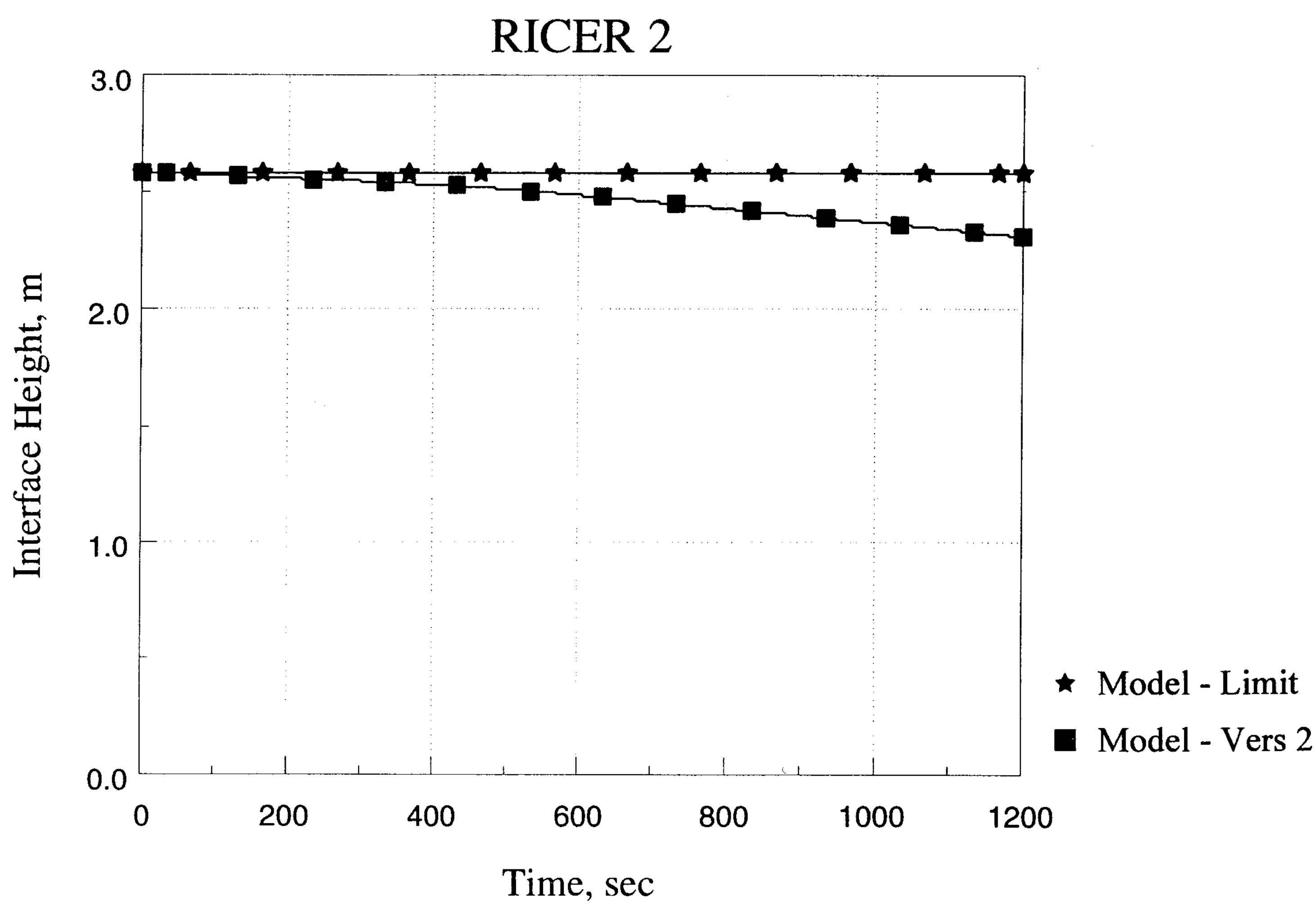


Fig. 18 - Comparison Between Model-Predicted Ricer 2 Interface Height With and Without Openings in Ricer 2 Deck and Around Ricer 2 Doors

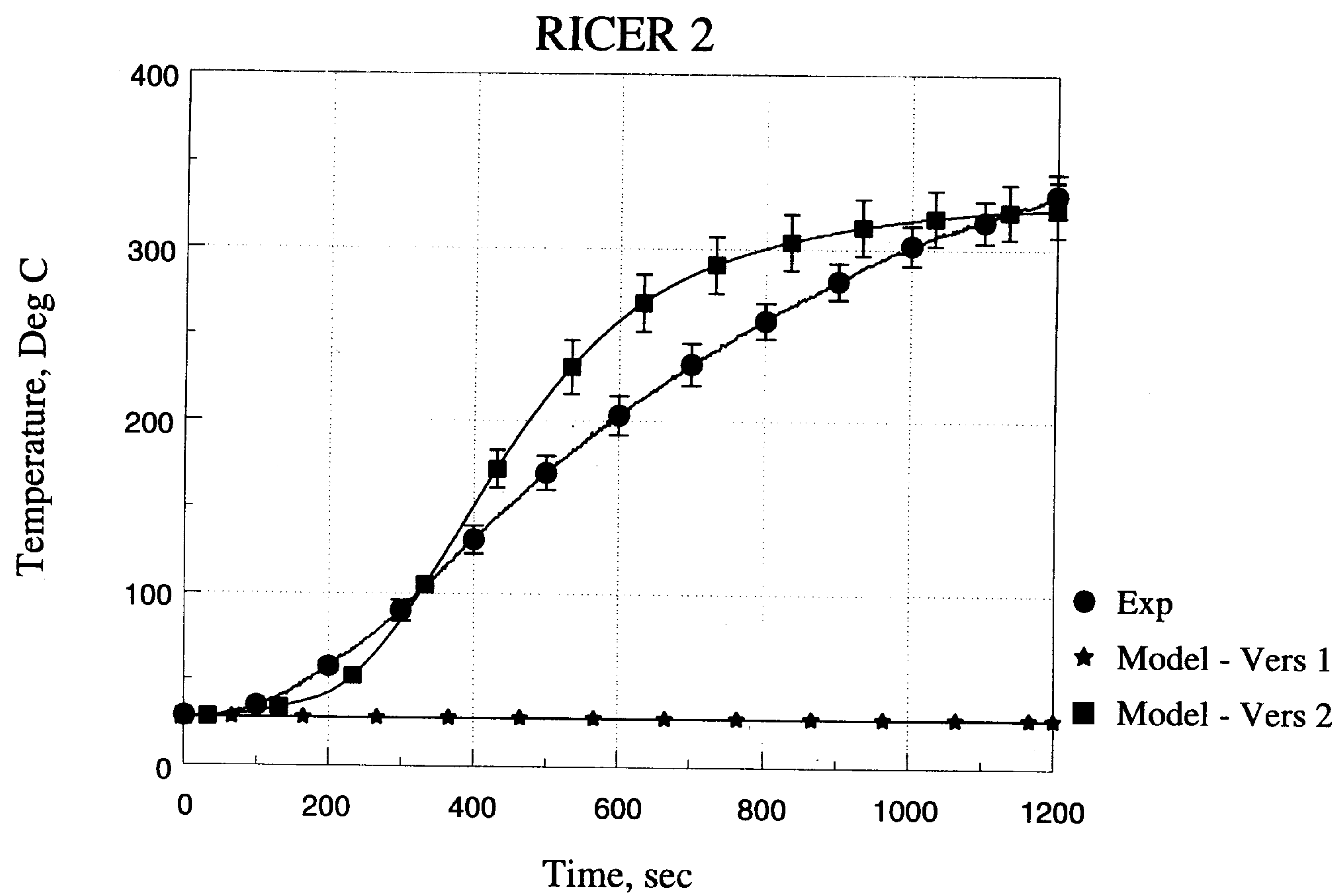


Fig. 19 - Model-Predicted Versus Experimentally-Determined Lower Layer Temperature In Ricer 2

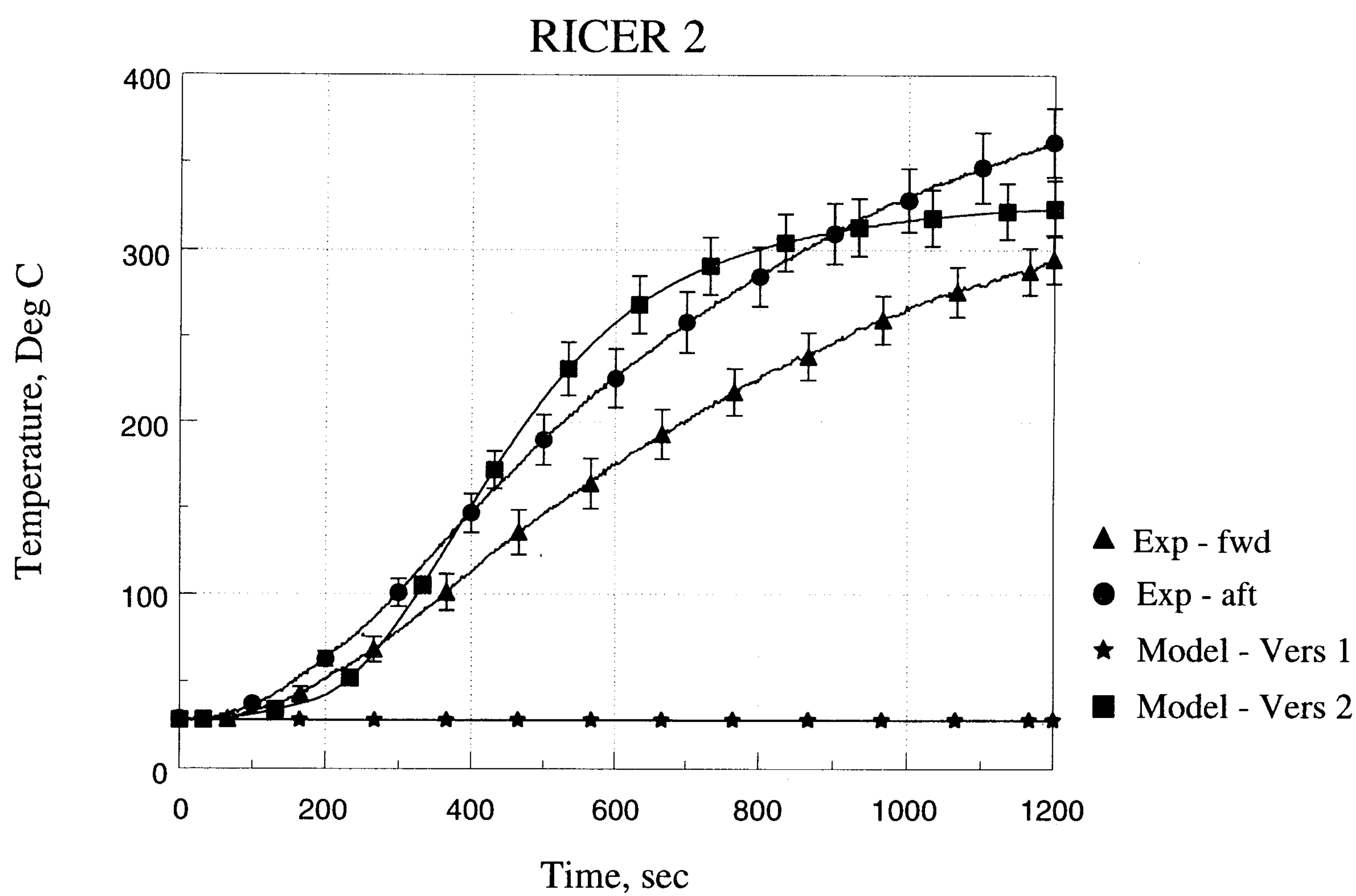


Fig. 20 - Experimentally-Determined Fwd and Aft Versus Model-Predicted Temperatures in Ricer 2

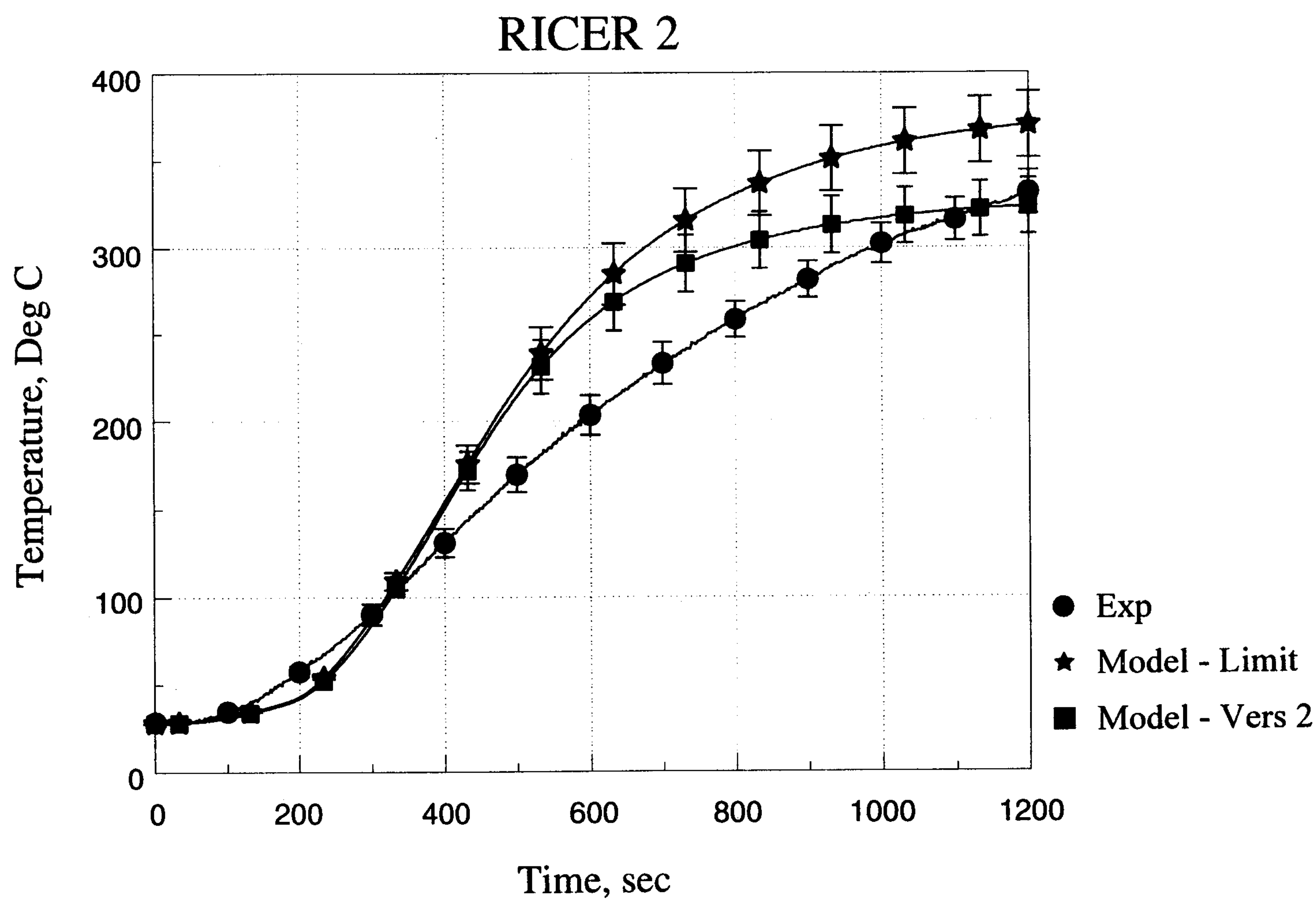


Fig. 21 - Comparison of Model-Predicted Lower Layer Temperature in Ricer 2 With and Without Openings in Deck and Around Doors

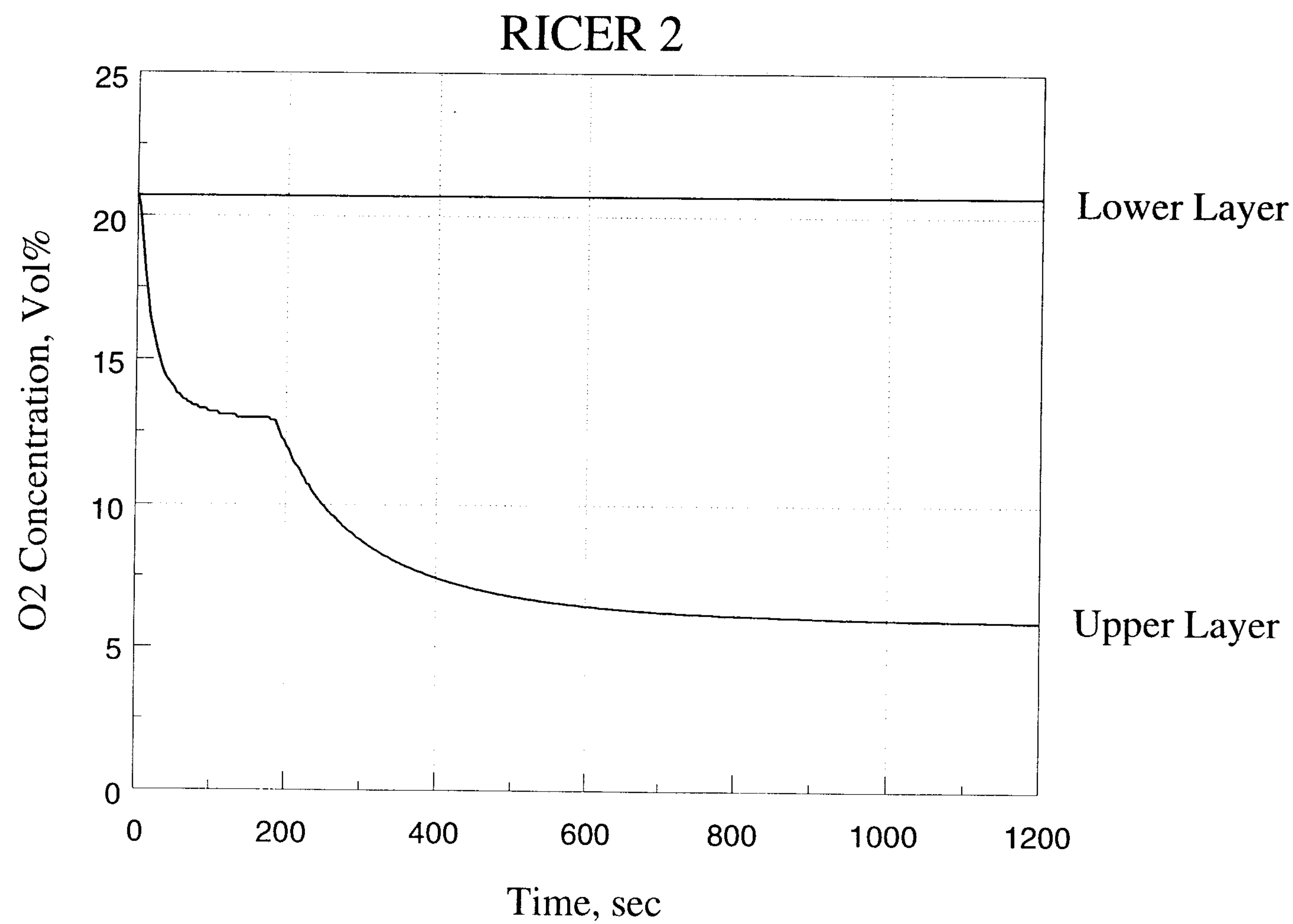


Fig. 22 - Oxygen Concentration in Ricer 2 Layers Using Model-Vers 2 and Assuming Openings in Ricer 2 Deck and Around Ricer 2 Doors

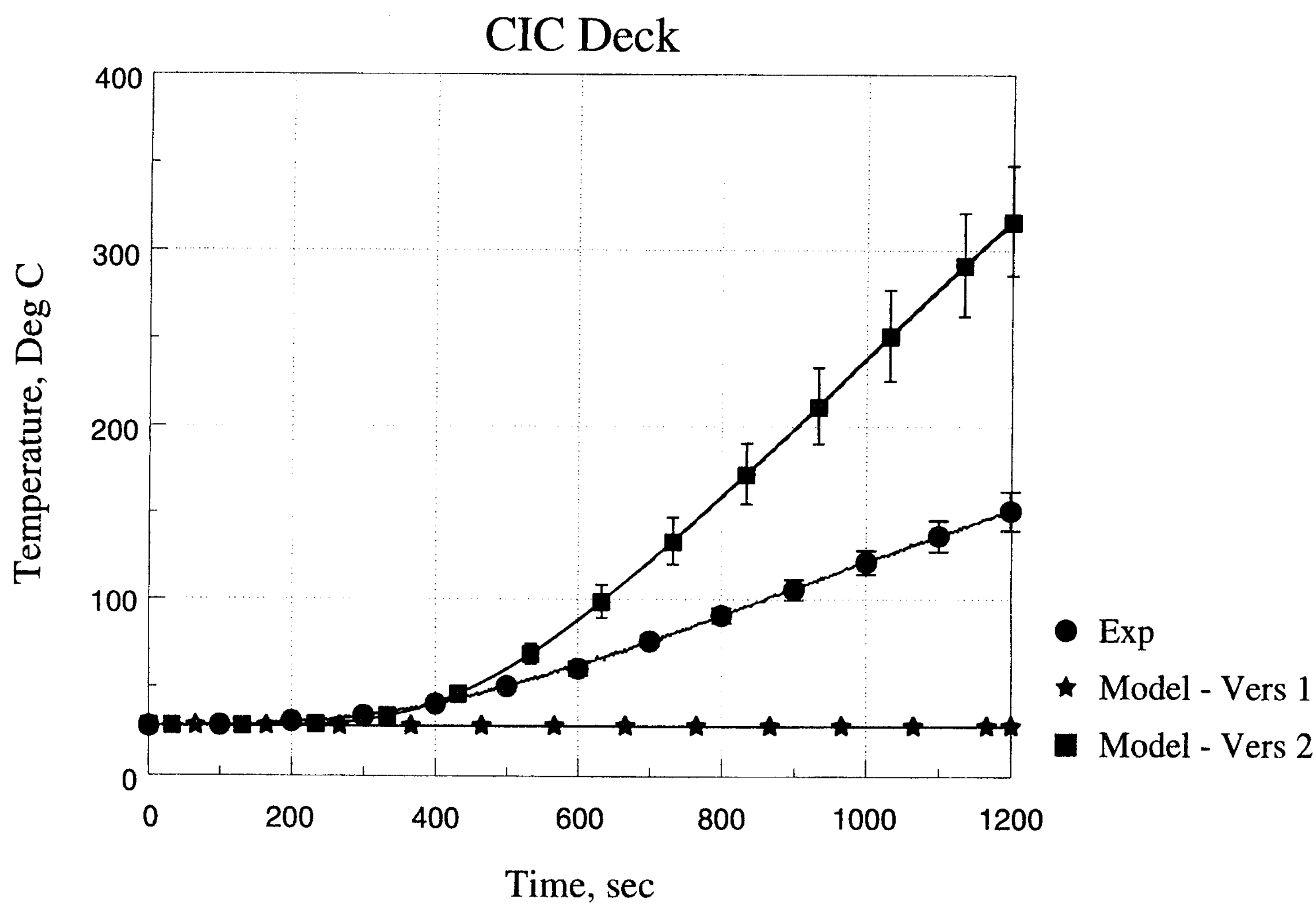


Fig. 23 - Model-Predicted Versus Experimentally-Determined CIC Deck Temperature

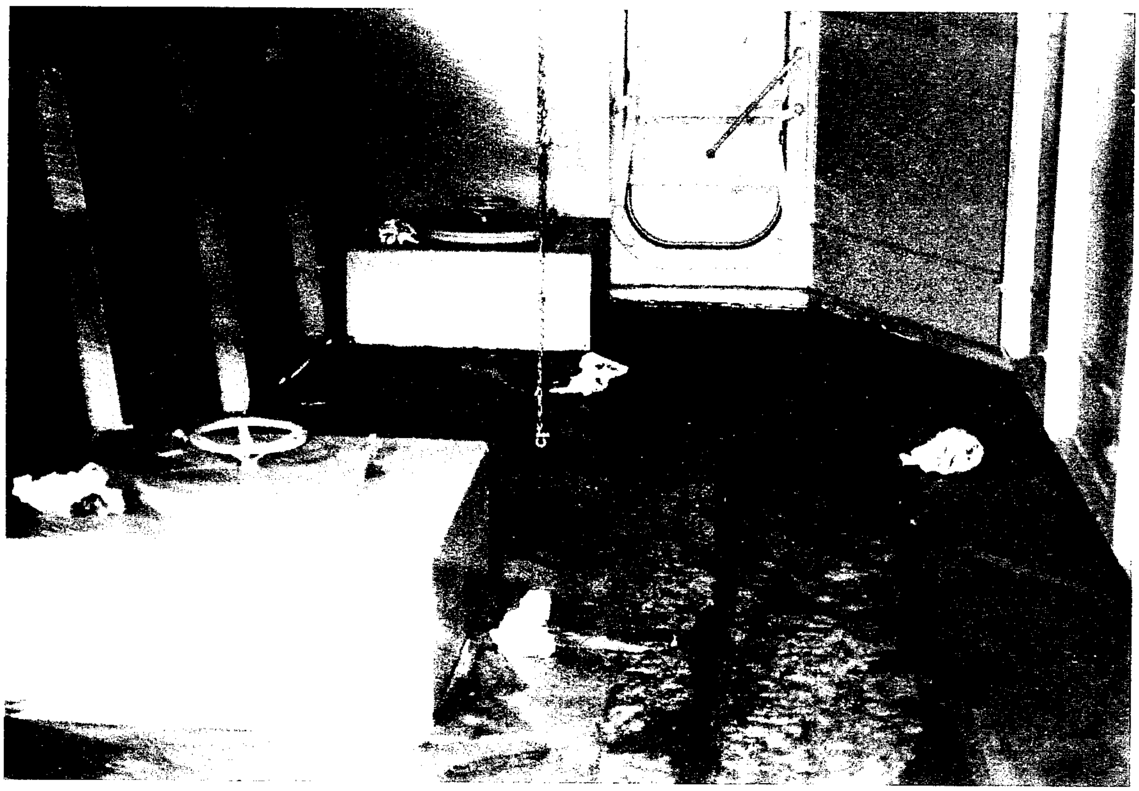


Fig. 24 - CIC Showing Raised Scuttles

(Figure from reference 7)

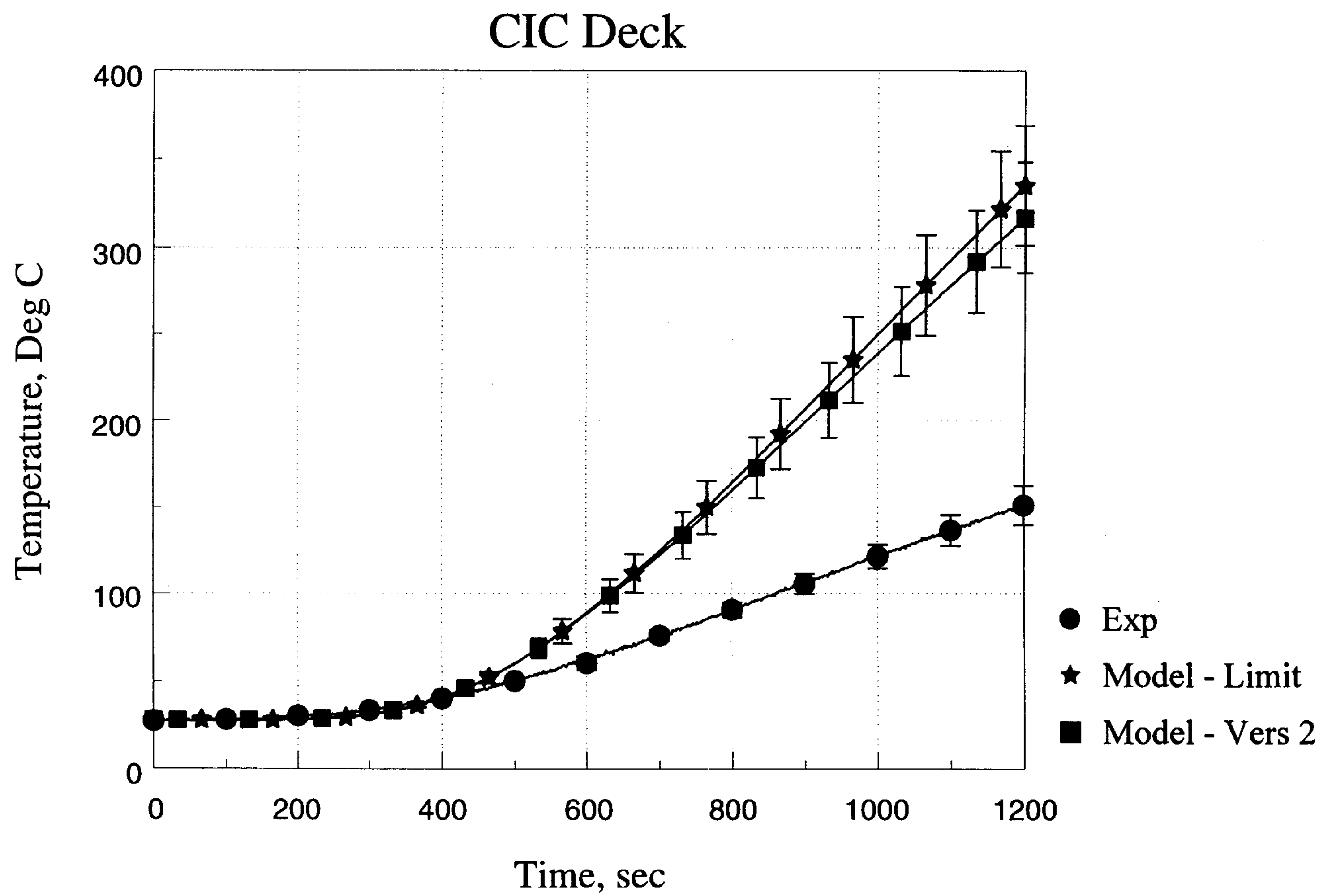


Fig. 25 - Comparison Between Model-Predicted CIC Deck Temperature With and Without Openings in Ricer 2 Deck and Around Ricer 2 Doors

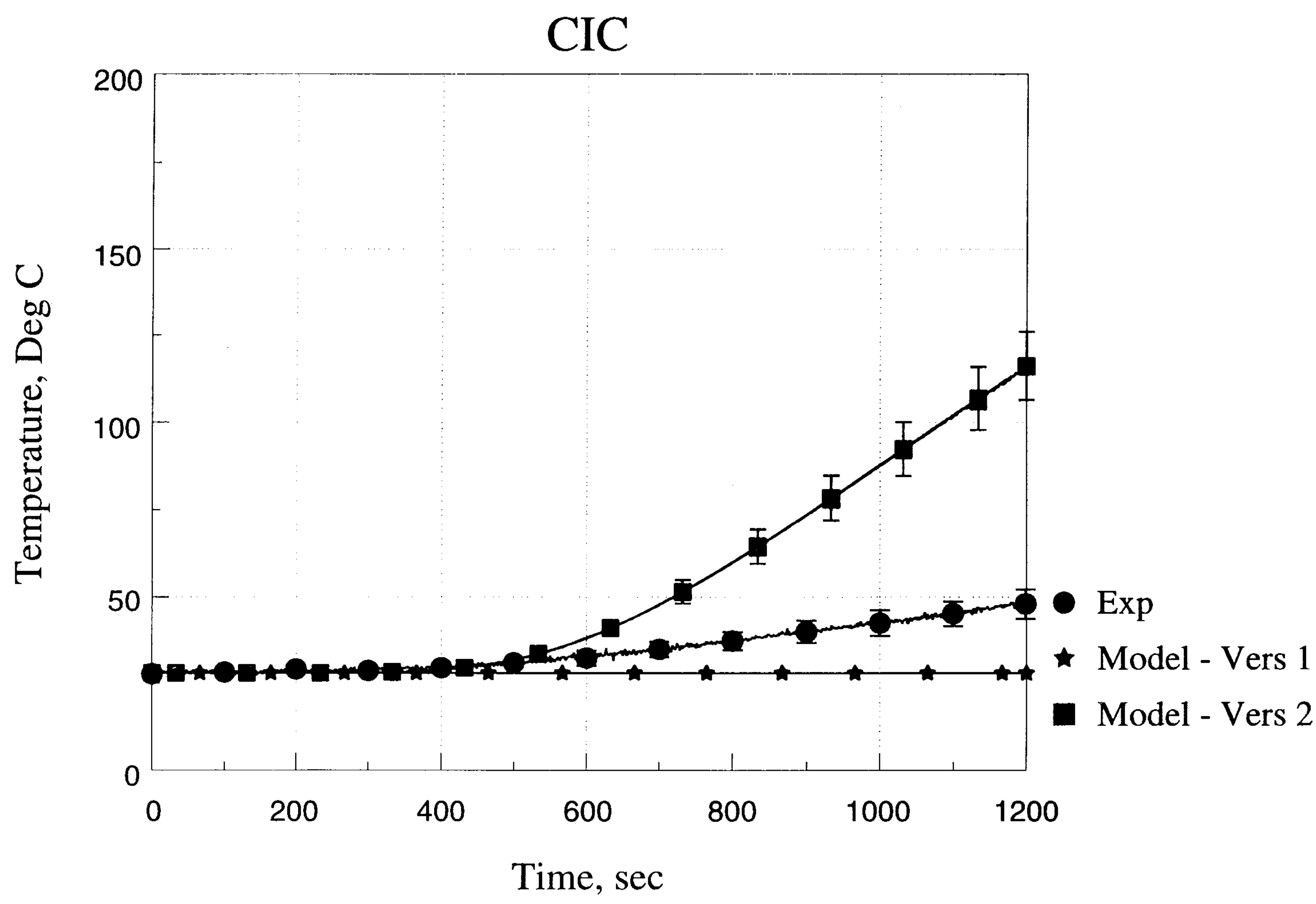


Fig. 26 - Model-Predicted Versus Experimentally-Determined CIC Lower Layer Temperature

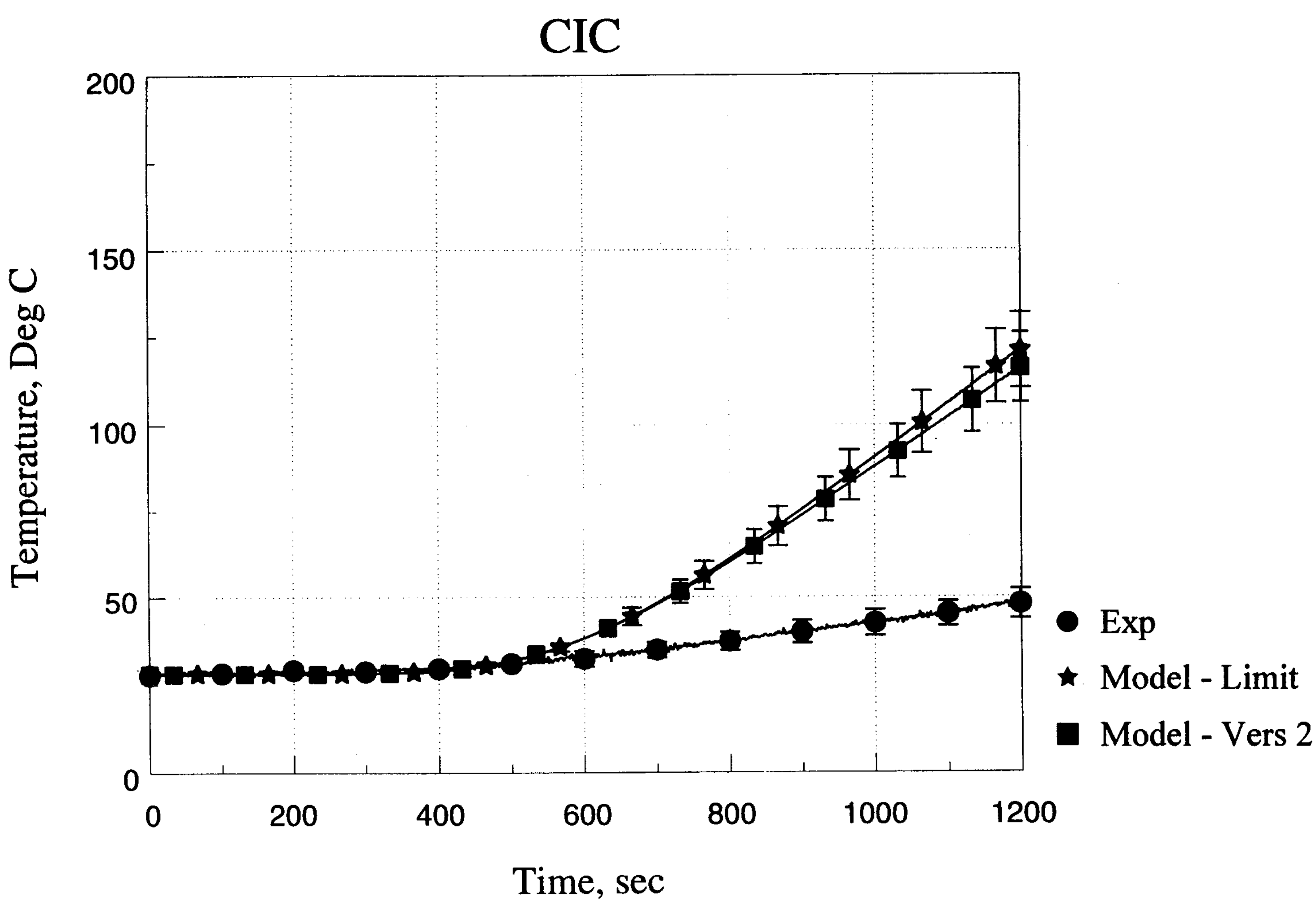


Fig. 27 - Comparison Between Model-Predicted CIC Temperature With and Without Openings In Ricer 2 Deck and Around Ricer 2 Doors

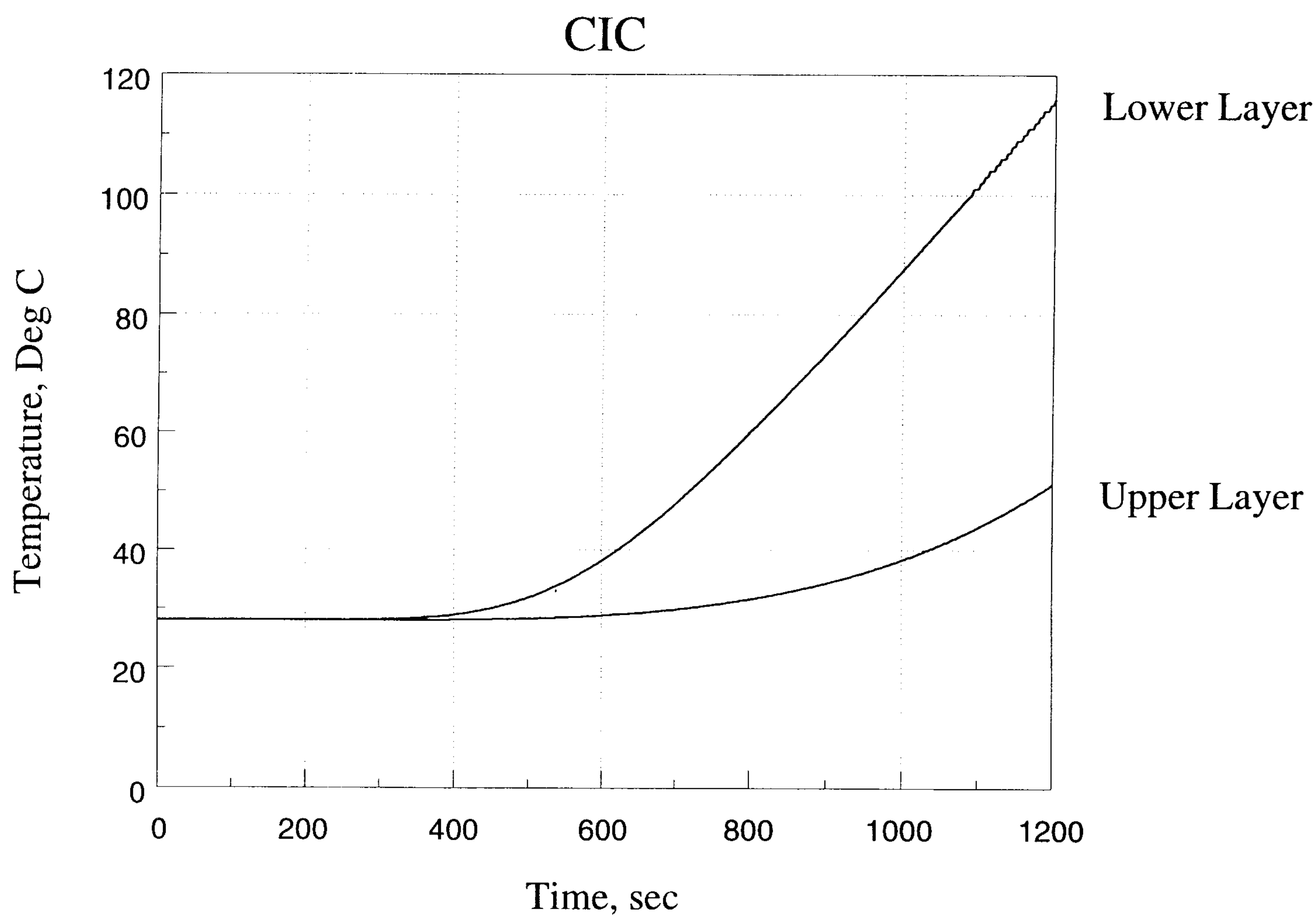


Fig. 28 - Upper and Lower Layer Temperatures in CIC Using Model-Vers 2 and Assuming Openings in Ricer 2 Deck and Around Ricer 2 Doors

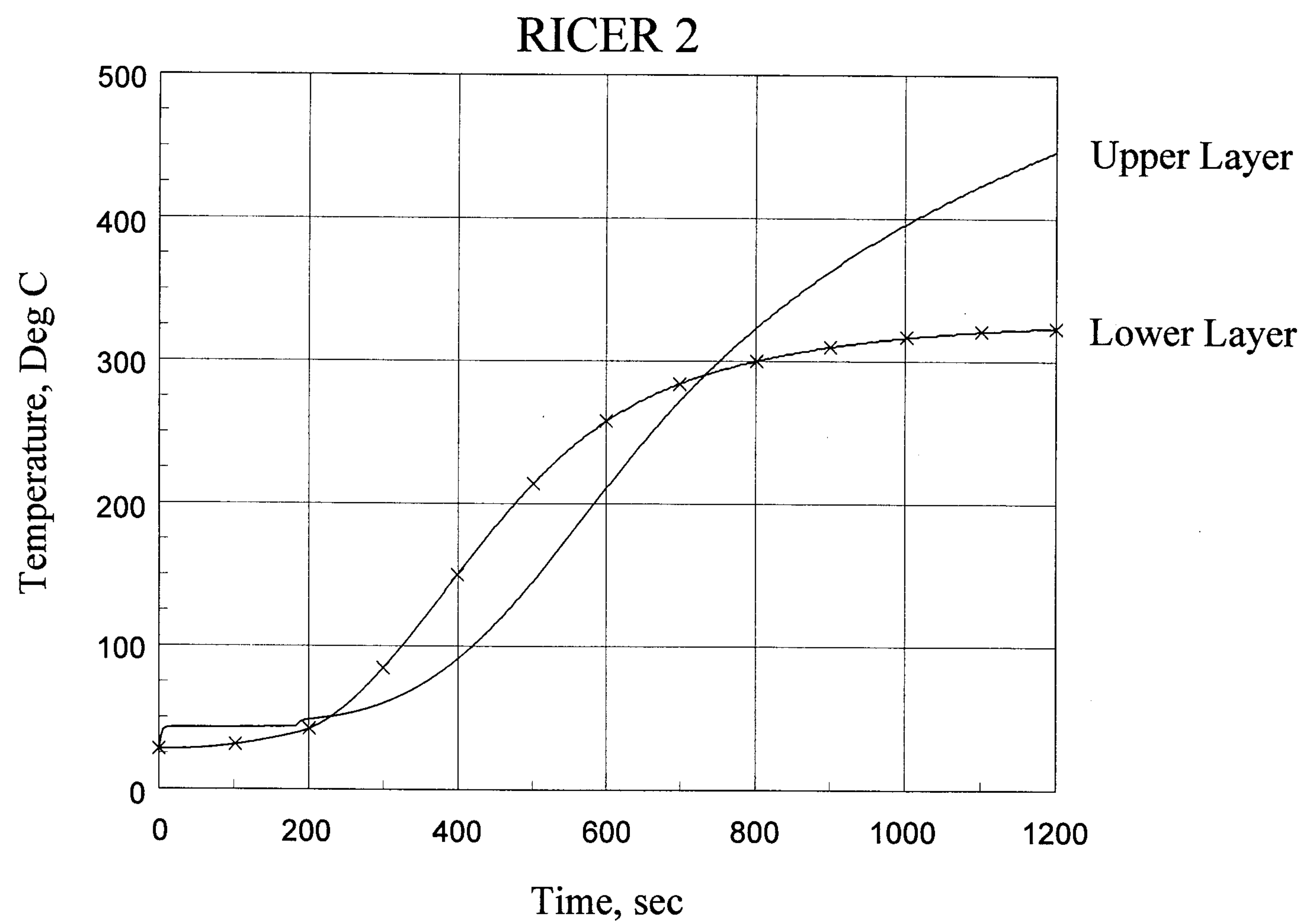


Fig. 29 - Upper and Lower Layer Temperatures in Ricer 2 Using Model-Vers 2 and Assuming Openings in Ricer 2 Deck and Around Ricer 2 Doors

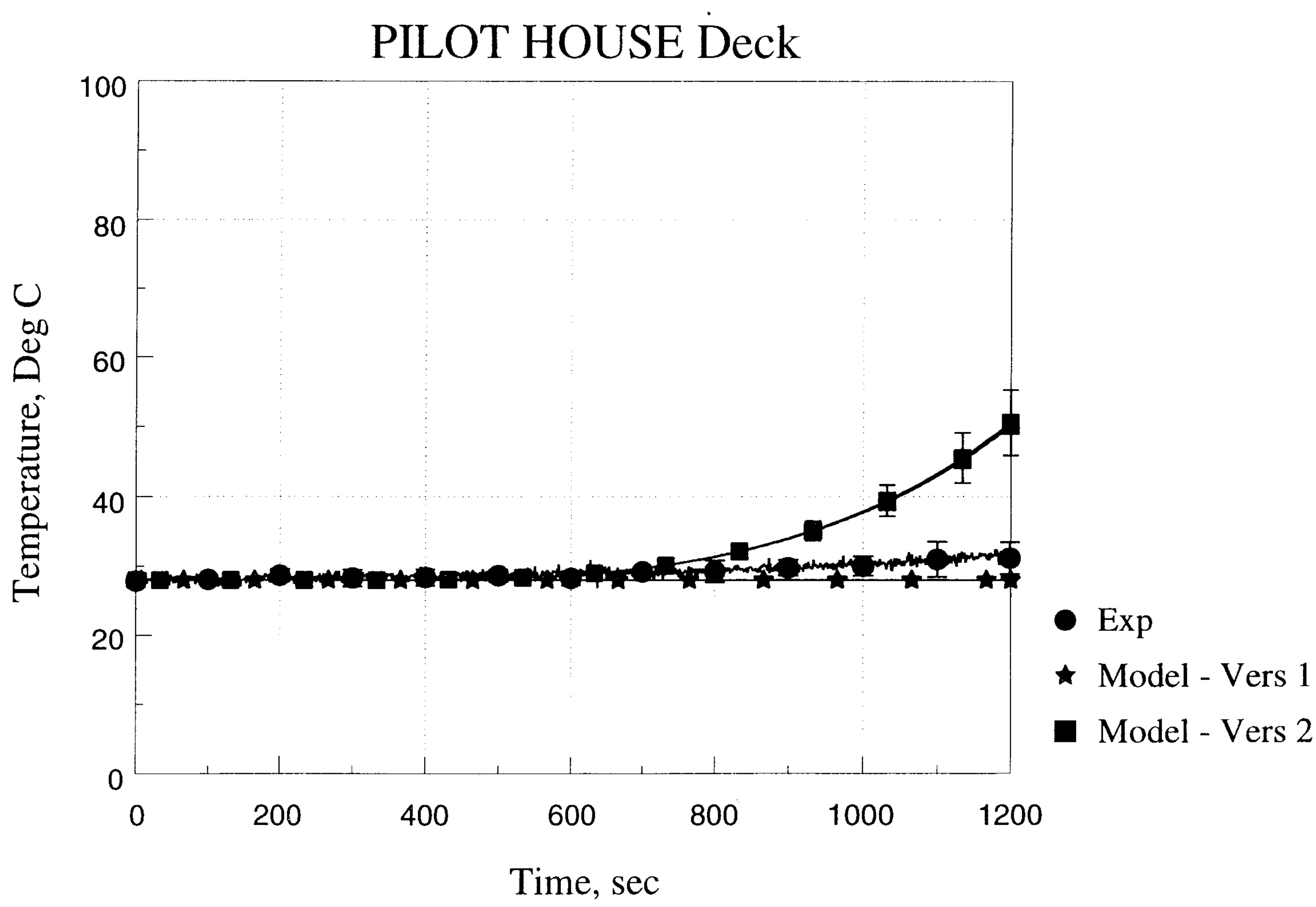


Fig. 30 - Model-Predicted Versus Experimentally-Determined Pilot House Deck Temperature

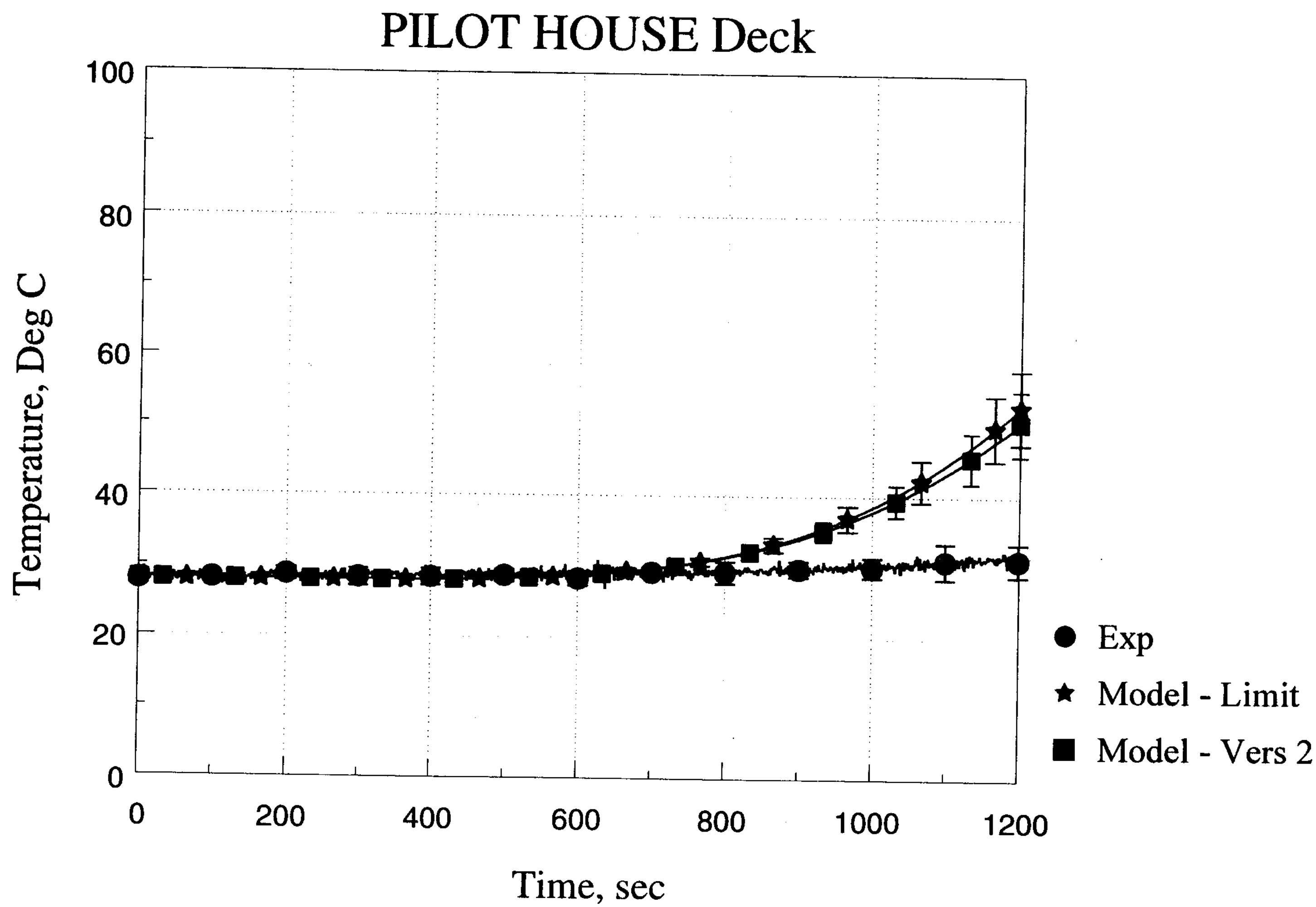


Fig. 31 - Comparison Between Model-Predicted Pilot House Deck Temperatures With and Without Openings in Ricer 2 Deck and Around Ricer 2 Doors

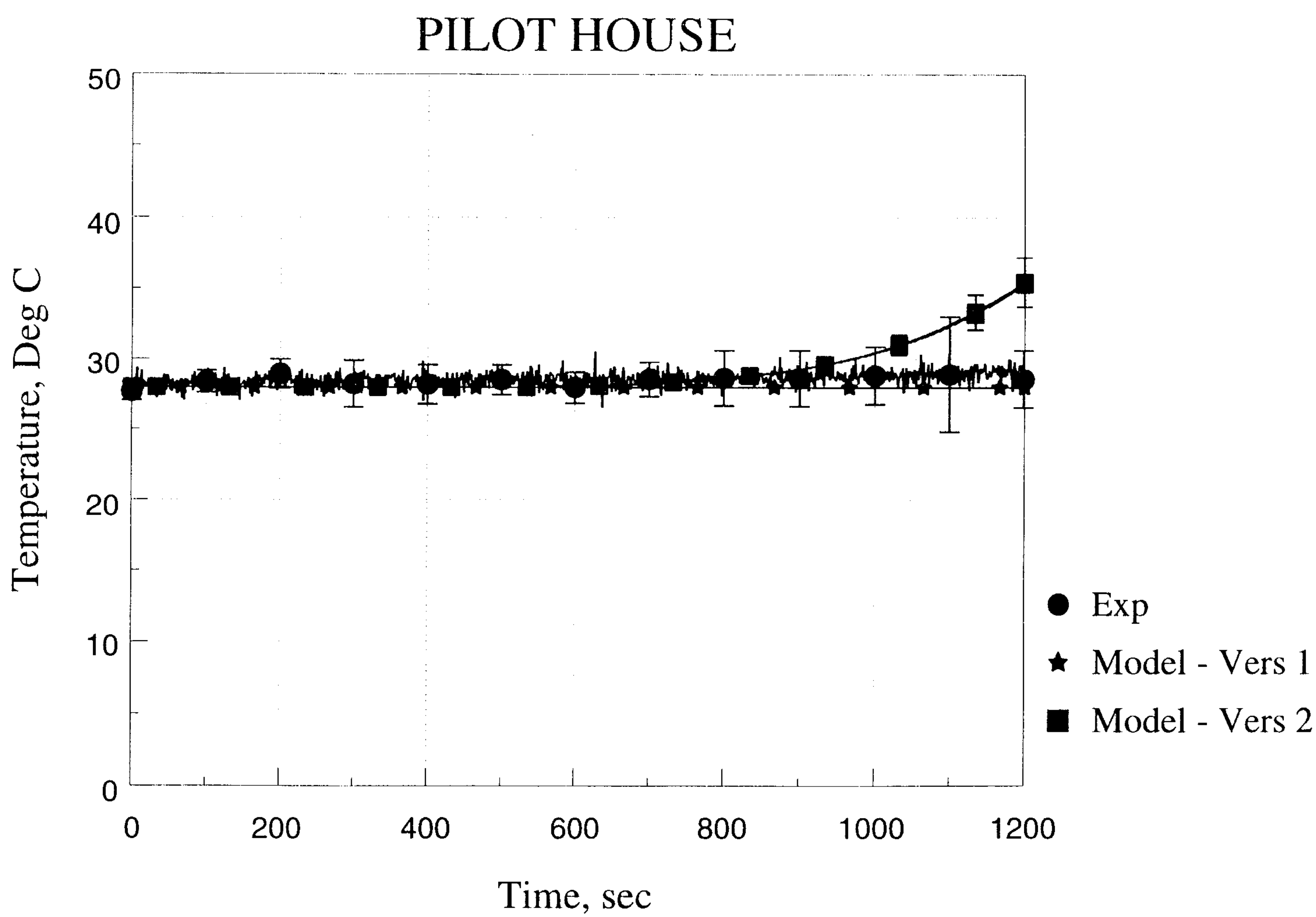


Fig. 32 - Model-Predicted Versus Experimentally-Determined Lower Layer Temperature in Pilot House

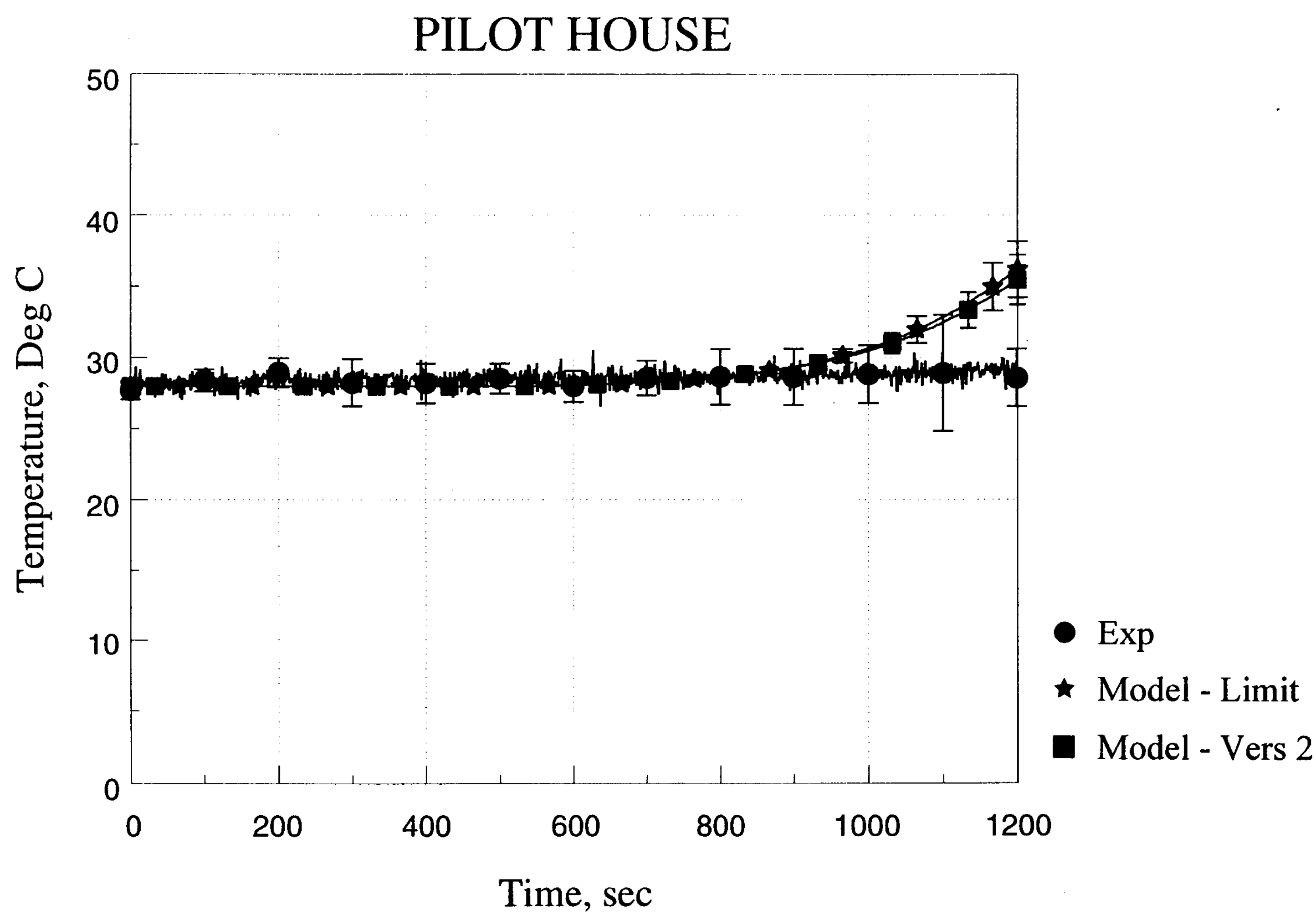


Fig. 33 - Comparison Between Model-Predicted Pilot House Temperature With and Without Openings in Ricer 2 Deck and Around Ricer 2 Doors